**LA-UR-94-1714**

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TITLE:

# In Situ Bioremediation: Cost Effectiveness of a Remediation Technology Field Tested at the Savannah River Integrated Demonstration Site

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SUBMITTED TO:

General Distribution, November 1994



Los Alamos

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Los Alamos, New Mexico 87545

FORM NO. 836 R4
ST. NO. 2629 5/81

# In Situ Bioremediation: Cost Effectiveness of a Remediation Technology Field Tested at the Savannah River Integrated Demonstration Site[1]

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# Executive Summary

The purpose of this report is to study the cost effectiveness of In Situ Bioremediation (ISBR) with horizontal wells as tested at the Savannah River Integrated Demonstration (SRID) site in Aiken, South Carolina. ISBR is an innovative new remediation technology for the removal of chlorinated solvents from contaminated soils and groundwater. The principal contaminant at the SRID is the volatile organic compound (VOC), trichloroethylene (TCE). A 384 day test run at Savannah River, sponsored by the U.S. Department of Energy, Office of Technology Development (EM-50), furnished information about the performance and applications of ISBR.

- The overall cost effectiveness of In Situ Bioremediation (ISBR) is based on the cost sensitivity of the biological component; as the biological addition increases, the cost per pound of VOCs remediated decreases.

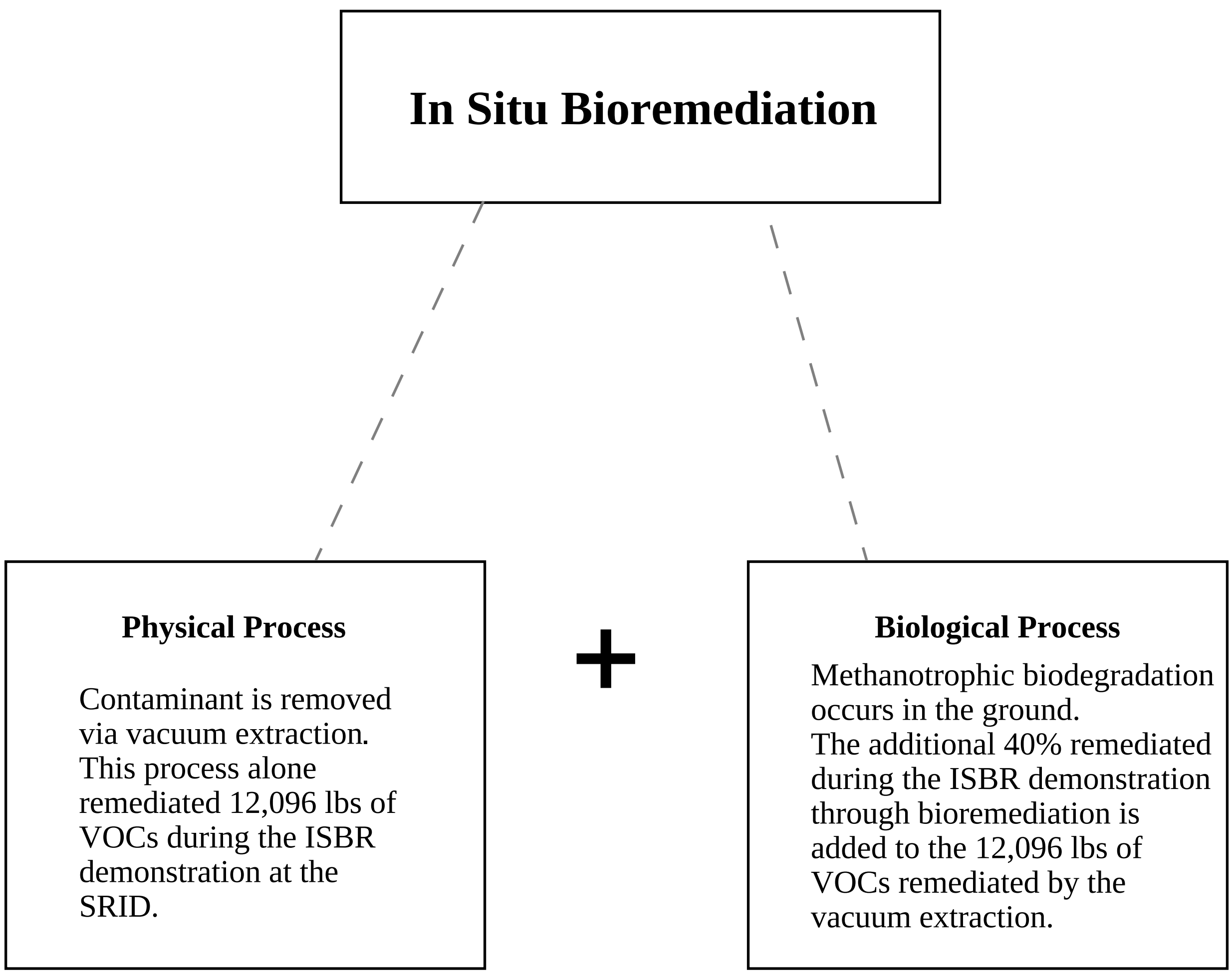
- The short-term cost of ISBR with a biological addition of 40% above the vacuum component is $21 per pound of VOCs remediated. The worse case scenario, ISBR + 0% addition costs $29/lb of VOCs remediated, and is based solely on the vacuum component.

- The baseline pump and treat/soil vapor extraction system costs $31/lb in the short-term and has no possibility of a biological addition.

- Life-cycle analysis shows that ISBR is more cost effective than the baseline pump and treat/soil vapor extraction system.
- As demonstrated, ISBR has a possible savings of $1 million at the SRID site alone.

In Situ Bioremediation is based on two distinct processes occurring simultaneously: the physical process of in situ air stripping and the biological process of bioremediation (see figure). Both processes have the potential to remediate some amount of contamination. A quantity of VOCs, directly measured from the extracted air stream, was removed from the test area by the physical process of air stripping. The biological process is difficult to examine. However, the results of several tests performed at the SRID and independent numerical modeling determined that the biological process remediated an additional 40% above the physical process. Given this data, the cost effectiveness of this new technology can be evaluated. In addition to calculating the cost effectiveness on the ISBR demonstration at the SRID, sensitivity analysis is conducted in order to determine how the overall cost of ISBR changes in regards to the performance of the biological component. By comparing the overall cost of this system and the price per pound of VOCs remediated against a conventional pump and treat/soil vapor extraction system, we can evaluate the overall cost effectiveness of the alternative technologies.

**Schematic Diagram of the Two Processes Involved in In Situ Bioremediation**



## System Caveats

The In Situ Bioremediation field demonstration at the SRID site is fully described in *Test Plan for In Situ Bioremediation Demonstration of the Savannah River Integrated Demonstration Project* [Hazen 92]. The ISBR demonstration at the SRID was set up to address a "hot spot" of an overall larger VOC contaminant plume.

The pump and treat/soil vapor extraction system is engineer designed and presumed to perform optimally. Both pump and treat and soil vapor extraction systems have been tested at the SRID. The baseline system (a combination of pump and treat/soil vapor extraction apparatus) is integrated to avoid overlapping of equipment and materials, and is located in an area exactly like the ISBR demonstration in regards to all necessary site characteristics, including overall concentration of contaminants. By designing both the baseline and the innovative systems to handle equal flow and assuming equal vacuum extraction performance, a level playing field for a cost comparison is created.

## Analysis

The data used in these analyses have a "field demonstration" level of confidence and are based on an actual field demonstration. The performance comparison consists of **Plan 1**, which is based on the new ISBR technology as demonstrated at the SRID, and **Plan 2**, which is based on "equivalent" conventional technologies, pump and treat/soil vapor extraction, necessary to remediate the contamination problems addressed by ISBR. Plan 2 is constructed so that it remediates the same conditions treated by ISBR at the SRID. In order to be fair to both technologies, equal physical process performance is forced from both Plan 1 and Plan 2. Plan 1 and Plan 2 are compared based on what it costs to operate them over equal periods of time. Performance data indicate that the vacuum component of ISBR destroyed 12,096 pounds of VOCs in 384 days, and an additional 40% above the vacuum component was destroyed by bioremediation. The vacuum component data is used in the pump and treat/soil vapor extraction system, assuming that the equal flow rates will remove the same quantity in an equal amount of time.

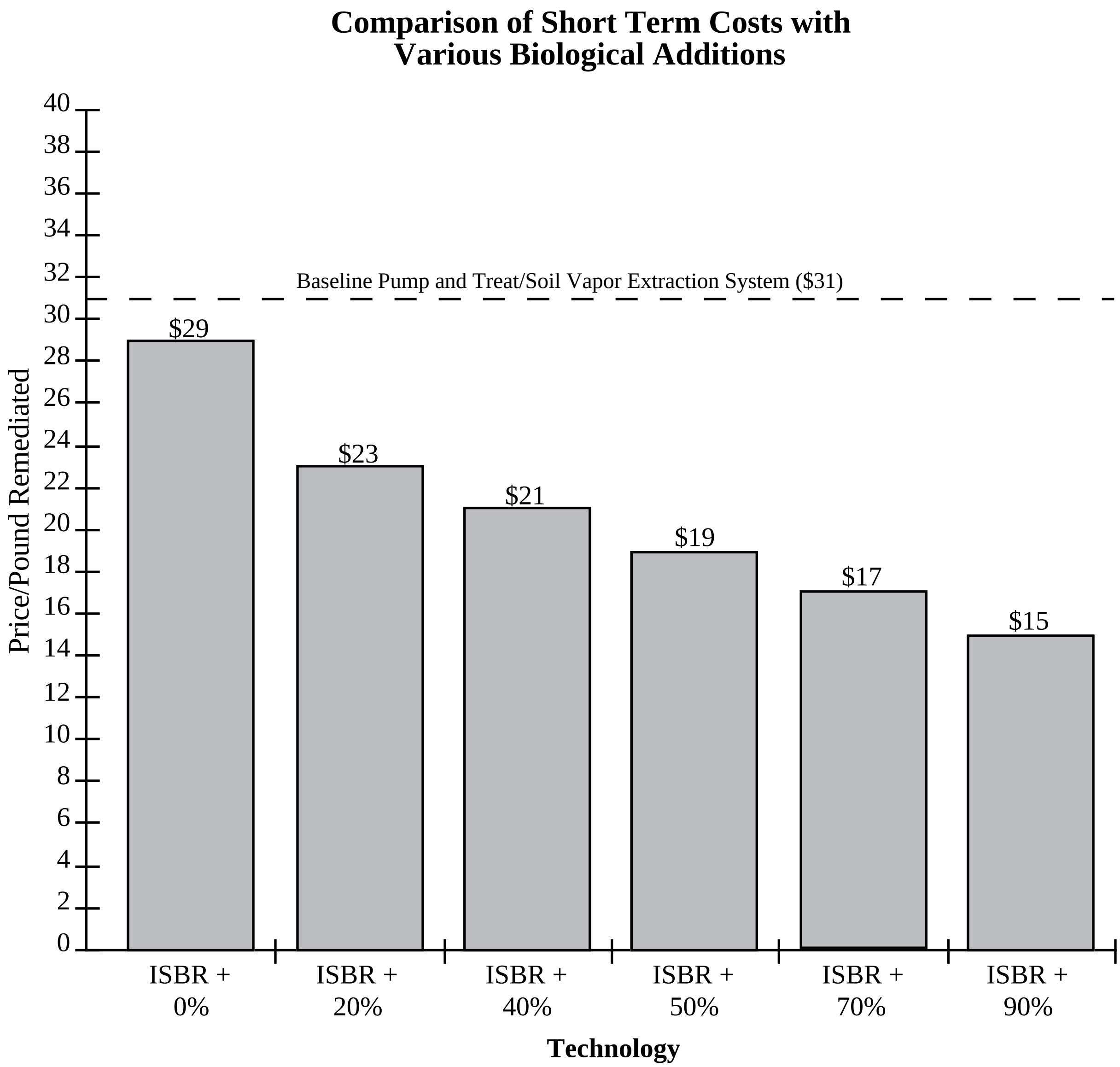
The ISBR system, as tested, uses two horizontal wells. The first well is an injection well, 300 ft long and 165 ft deep (about 35 ft below the water table). The second well is an extraction well, 175 ft long and 75 ft below the surface (in the vadose zone). A concentration of methane (between 1% and 4%) and any necessary chemical nutrients (nitrogen in the form of nitrous oxide and phosphorus in the form of triethyl phosphate) are blended into the injected air stream to create a biological element for remediation. The methane provides the necessary material substrate for the indigenous microorganism to produce the enzyme methane monooxygenase which, in turn, degrades the principal contaminant, trichloroethylene (TCE). For the conventional technologies used in Plan 2, four vertical SVE extraction wells are assumed to be equal in area influenced to the one horizontal extraction well of ISBR. One vertical pump and treat well is also used. Volatilized contaminants from both remediation systems are sent to a catalytic oxidation off-gas system where they are destroyed.

Economic comparisons for short-term costs are made by relying on actual field data and using cost sensitivity analysis; life-cycle costs are estimated in relation to possible time to achieve cleanup. The first economic comparison is a calculation of the short-term costs in relation to performance. Short term costs are those expenses incurred during the immediate field test demonstration of the technologies compared (generally about a year). The equipment capital costs are amortized yearly over the useful life of the equipment, which is assumed to be 10 years. All short-term equipment costs are amortized at 7%, which is the interest on the loan.

For ISBR there is a total cost of about $354,000 with total 16,934 pounds of VOCs being destroyed by the vacuum component and biological component, giving a cost per pound of VOCs remediated at about $21. The integrated pump and treat/soil vapor extraction with 4 vertical SVE wells has a total cost of about $380,000. Assuming an equal vacuum extraction performance of 12,096 pounds of VOCs removed, the integrated system has a cost per pound of VOCs remediated at about $31. A ratio of ISBR to the baseline shows that ISBR is 32% less expensive than the baseline.

Next, an analysis of life-cycle cost is conducted. A real discount rate of 2.3% is used to calculate the present value. ISBR, with its combination of vacuum component and bioremediation, costs $1 million and remediates the site in only 3 years. The baseline takes 10 years to remediate the site and costs $2 million. ISBR, therefore, saves $1 million and 7 years of remediation. Even when we assume the baseline can perform at twice the expected time and cleans the site in only 5 years, it still costs $1.4 million. ISBR still beats the baseline by $400,000 and 2 years remediation time.

Where ISBR has the potential to exceed the baseline technologies is its ability to remediate a portion of the contamination *in situ*, thereby eliminating the need to physically remove the contaminant and process it. Since ISBR relies heavily on the biological component to achieve greater performance, sensitivity analysis is conducted to compare the cost per pound of VOCs remediated versus the performance of the biological component. Of particular interest is ISBR + 0% addition. This is a **worse case** scenario based on a 0% addition from the biological component. It assumes that all the necessary materials are added to stimulate the biological addition, but no additional remediation occurs. In this situation, ISBR still costs slightly less than the baseline, $29 versus $31, respectively. By adding a percent addition of pounds of VOCs destroyed by bioremediation in addition to that removed via the vacuum component, we can examine how the cost per pound changes with respect to the biological component. Six hypothetical percentages are used to account for the bioremediation levels: 0%, 20%, 40%, 50%, 70%, and 90%. The following figure shows the various hypothetical additions and the decrease in cost per pound of VOCs remediated.




The baseline technologies in Plan 2 have a constant price per pound of VOCs remediated of $31 because there is no biological component. As the biological addition of ISBR increases, the price per pound of VOCs decreases. So, even in the worse case scenario where no bioremediation occurs, ISBR breaks even with the baseline. There is, therefore, no cost risk to run ISBR over the baseline system. The savings, however, are quite substantial when the biological component is stimulated. In order for the biological component to occur, it is necessary to inject methane and nutrients into the system. Without this material, only the physical, vacuum component of ISBR is possible. Because the cost of the biological component is so inexpensive, ISBR only has to remediate an additional 1,570 lbs of VOCs over the 12,096 lbs of VOCs remediated with the vacuum component in order for the system to completely pay for the cost of the methane injection. Any additional remediation is achieved at no extra cost and increases the cost savings of ISBR over the baseline technologies.

Next, the total present value cost for operating each plan for five years, including all necessary equipment, is computed. The total equipment costs are included in the first year so that no amortization is needed. As with the short-term cost, the potential cost-savings for ISBR lie with its ability to remediate VOCs in additon to the physical process, thereby lowering the cost per pound and increasing the total amount remediated over equal time. The same hypothetical percent additions of 0%, 20%, 40%, 50%, 70%, and 90% are used. The table below shows the decrease in price per pound as bioremediation increases. The $38 per pound of VOCs remediated with the pump and treat/soil vapor extraction remains constant because there is no equivalent biological addition.

**Life-Cycle Cost of ISBR over Five Year Operation in Comparison to Percent Addition**

| Hypothetical percent addition | Physical component from Life cycle costs (lbs) | Additional Pounds remediated via biological component | New Total pounds VOCs remediated | Price per pound VOC remediated |
|---|---|---|---|---|
| 0% | 37,375 | 0 | 37,375 | $38 |
| 20% | 37,375 | 7,475 | 44,850 | $31 |
| 40% | 37,375 | 14,950 | 52,325 | $27 |
| 50% | 37,375 | 18,688 | 56,063 | $25 |
| 70% | 37,375 | 26,162 | 63,537 | $22 |
| 90% | 37,375 | 33,638 | 71,013 | $20 |

## Perspectives and Cost Drivers

The two largest categories in regards to cost for both ISBR and the baseline system are the costs of consumables and labor. The labor and consumables are greater than 85% of the overall operating costs;

therefore, if the overall remediation time of the project is shortened, the cost will drop. This is due to the nature of the labor and consumables which are incurred each day of operation. Since ISBR can significantly decrease operation time, ISBR lowers the overall cost of the remediation effort.

## Applicability

ISBR can be very effective in settings where some interbedded thin and/or discontinuous clays are present. ISBR should prove even move successful than in situ air stripping alone because ISBR contains a biological component as well as the physical air stripping process. A potential concern with the use of ISBR is the possible lateral spread of the contaminant plume. If the geology constricts vertical flow, the injection process can push the dissolved contamination concentrically from the injection point. Thus, it may be advisable in heterogeneous formations to use ISBR in conjunction with a surrounding pump and treat system that provides hydraulic control at the site. Note that the limitations on applicable geologic settings described above also apply to soil vapor extraction and pump and treat systems.

# 1. Introduction

One of the most prevalent environmental remediation problems facing the United States today is the contamination of soils and groundwater with chlorinated organic solvents. For years, the compounds trichloroethylene (TCE) and tetrachloroethylene (PCE) were the major industrial degreasing and cleaning solvents used. TCE is known to be the most prevalent pollutant existing in Superfund sites [Keeler 91].

The Savannah River Integrated Demonstration (SRID), located at the U.S. Department of Energy (DOE) Savannah River Site, near Aiken, South Carolina, is a series of demonstrations of new environmental technologies and remediation systems. The demonstration, testing, and evaluation of such new environmental remediation methods play an important role in the campaign to clean up the nation's waste sites. New remediation technologies and systems are expected to prove more effective and less expensive for restoring sites with environmental contamination. At the SRID, methane was injected into the subsurface to stimulate the indigenous microorganisms to degrade the TCE in place. This process is known as *in situ* bioremediation.

Previous reports [Henriksen 93; Booth 91; and Schroeder 92] outline the methodology used here for evaluating the cost effectiveness of a new environmental technology. First, a performance comparison is made between the new environmental technology and a similar or related conventional technology (i.e., one used in common practice). A scenario is constructed to provide an equal playing field for both systems. This scenario considers the remediation of a site by using either the new ISBR technology (Plan 1) or the conventional baseline pump and treat/soil vapor extraction system (Plan 2). Finally, an economic comparison is made between the plans. We believe a careful assessment of the performance of the new technology is critical to understanding its economic potential.

The cost-effectiveness analysis of a new environmental remediation system such as in situ bioremediation with horizontal wells poses numerous challenges. The prevailing issues are similar to those discussed in Schroeder 92:

- Depth of understanding of performance issues

  Field data from the ISBR demonstration will be used to describe the performance of the system. As such, the performance scenario constructed in this study is a simple, although still useful, estimate. Ongoing efforts in analytical and numerical modeling of the ISBR system will provide further insight [Travis 94]. Through such modeling, the subsurface processes at the Savannah River Site (SRS) can be better understood. Also, modeling can be used to extend results and insight to other sites with different subsurface parameters. In addition to modeling, analysis of the SRID pre- and post-test characterization data will add to the understanding of ISBR performance.

• Extrapolation of performance data

In using field data from the SRID demo we have a limited history of observable performance: the ISBR demonstration had an actual run time of 384 days. However, in the evaluation of a new remediation technology we are interested in its performance over a time span of years. Thus, the problem is to make reasonable long term extrapolations of performance based only on short-term field tests.[2]

• No single technology can accomplish all cleanup goals

In Situ Bioremediation with horizontal wells is proposed as one more “tool” in the “toolbox” of technologies for environmental restoration (ER). That is, it is important to recognize that no one new technology is viewed as the solution to all ER problems. Each ER site is distinct in terms of its geology, hydrology, type of contamination, cleanup goals, etc., Because of these site differences, no one new technology can be expected to revolutionize the remediation business in terms of cost. Nevertheless, significant cost savings may be achievable by use of new technologies. Thus, in this cost-effectiveness study we will emphasize that the economic value of ISBR is closely tied to its use in appropriate application areas.

• Demonstration versus full-scale design and wide application

The Savannah River Integrated Demonstration program provides only a *demonstration* of a new technique. It cannot, by definition, answer all questions about the performance of a new technology. One obvious value of a demonstration is to learn how to apply the technology better the next time. In this study we create a performance scenario closely tied to the field demonstration in order to capitalize on the valuable data and knowledge gained through the SRID. However, this study also qualitatively discusses the use of the technology in a broader sense. For example, recent developments in numerical modeling provide alternatives to traditional methods of system operations and possibilities in the area of technology optimization . The aim is to take advantage of the knowledge gained through the SRID demonstration, but not to handicap the new technology by overly relying on the exact parameters and methods used in the actual SRID field test. Where the use of new drilling techniques, well geometries, etc., can be expected to favorably impact the cost effectiveness of ISBR, we point this out.

In addition to the performance and economic comparisons between ISBR and conventional technologies described above, other general issues about ISBR are presented in Section 8 of this report. These qualifiable issues are: applicable geologic settings, applicable waste sites, monitoring requirements, health and safety issues, regulatory approval, and technology optimization. These issues are not easily quantified into discrete performance and economic scenarios; nevertheless, they are vital to the future technical success and cost effectiveness of ISBR, as well as other environmental remediation technologies.

## 2. Methodology

The methodology used to evaluate the cost effectiveness of a new environmental technology is composed of both a performance evaluation and an economic evaluation. The key performance question in this study is the cost sensitivity of the ISBR biological component to affect the overall cost of the remediation process. Previous studies outline the cost-effectiveness methodology in detail [Henriksen 93; Booth 91; Schroeder 92]. The steps of the methodology are shown in Figure 1. The new environmental technology will be compared to baseline technologies currently in use. We are addressing the question: “For the remediation of soils and groundwater contaminated by chlorinated solvents, how much money can be saved by using in situ bioremediation with horizontal wells instead of conventional technologies?”.

We must emphasize the importance of the performance evaluation in this methodology. Performance issues are critical in establishing a balanced comparison from which the economic cost savings of the two (or more) alternative technologies can be computed. Without a reasonable performance assessment, the ensuing economic analysis will be of little value.

A fundamental issue in evaluating a new environmental technology is to address the question, “What does one compare the new technology *to*?”. It is important to note that in many cases a new environmental technology does not specifically replace some current technology or practice on a one-to-one basis. Thus, we will look at a range of baseline technologies, if necessary, to reasonably consider the actual role of the new environmental remediation technology. The challenge is to analyze information on diverse techniques in a fashion that will lead to a fair and reasonable assessment of the cost effectiveness of the new technology. Given this goal, the major components of the methodology, as discussed in Schroeder 92, are:

- Identify major performance characteristics of the new environmental technology.

- Identify appropriate conventional technologies to serve as the baseline for performance comparisons with the new technology.

- Compare performance between the new technology and the conventional alternatives.

- Use scenarios to provide a realistic context for the performance comparison.

- Perform an economic comparison of the new technology and the conventional alternatives. Use the above constructed scenarios for detailed cost-savings analysis on a life-cycle basis.

- Assess uncertainty in performance, cost, and regulatory permitting.

- Consider all other relevant aspects and/or effects involved in the use of the new environmental technology. When it is not possible to consider these influences in scenarios due to a lack of detailed information, a qualitative discussion is given. Important issues are: future developments expected in both the new technology and conventional alternatives, applicability of the technology to different geologic settings, applicability of the technology to different types of waste sites, health risk and environmental risk reduction, and regulatory status and perceived public acceptance.

We intend for this report to be a useful tool for managers of DOE environmental restoration programs, government agencies and private industry; however, the reader will need to pay careful attention to caveats discussed in this report, such as applicable geologic setting, to determine how this technology can best be utilized at a particular environmental restoration site. It is beyond the scope of this report to consider all possible scenarios. Consequently, the descriptive approach provides the most general use for the DOE community. It is for these reasons that any specific conclusions drawn in this report from data obtained at SRID must be regarded as best applicable to the Savannah River Site only. Any and all applicable characteristics associated with that specific site are significant factors used to determine the outcome and evidential success of any ER technology studied.

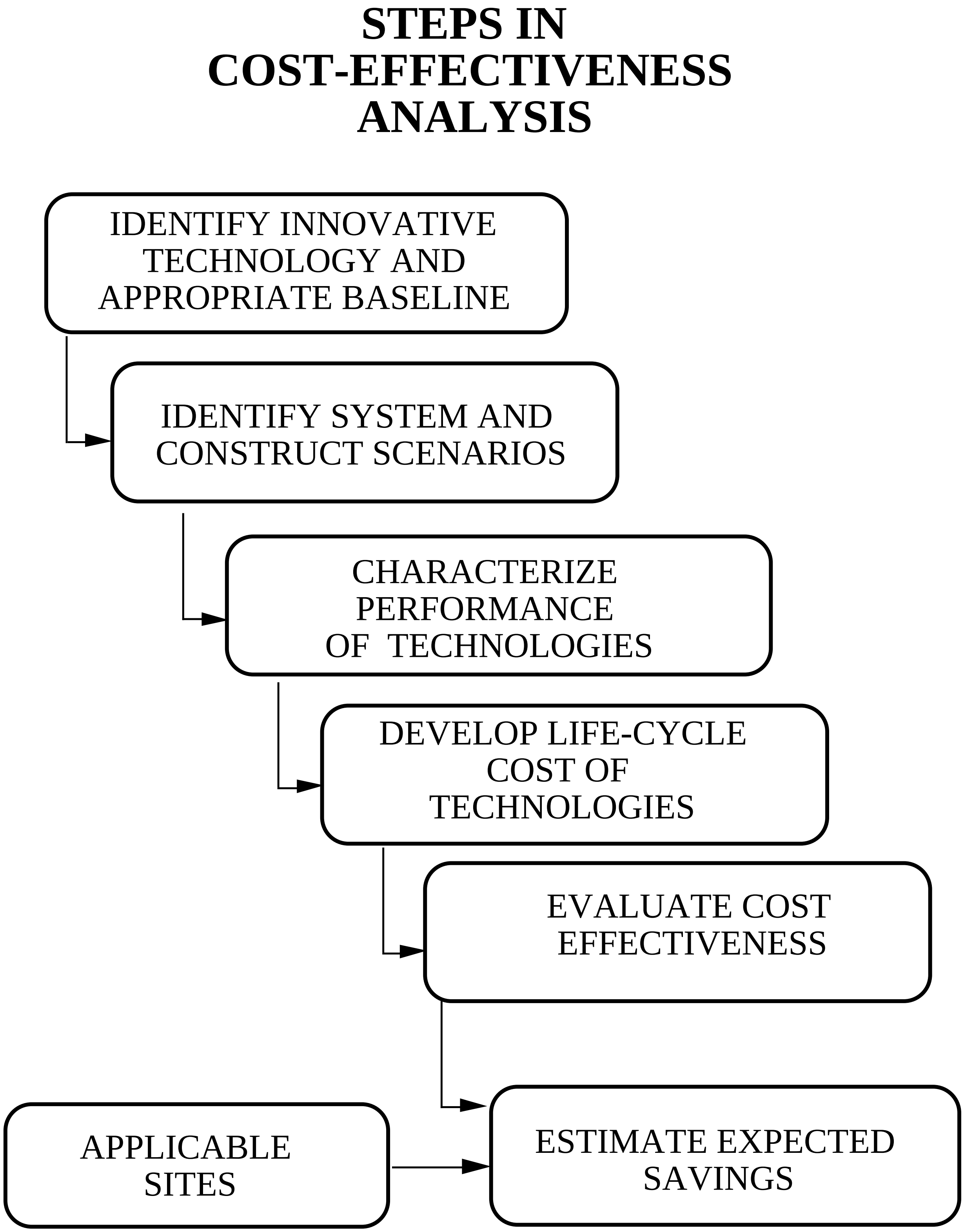



**Figure 1: Steps in Cost-Effectiveness Analysis. Taken from Booth 91.**

# 3. Description of In Situ Bioremediation

## 3.1 In Situ Bioremediation Demonstration at the Savannah River Integrated Demonstration Site

The In Situ Bioremediation field demonstration at the SRID site is fully described in *Test Plan for In Situ Bioremediation Demonstration of the Savannah River Integrated Demonstration Project* [Hazen 92]. Throughout this report, we refer to In Situ Bioremediation (ISBR) demonstration as meaning "in situ bioremediation using horizontal wells." The ISBR demonstration took place within the bounds of the Integrated Demonstration (ID) site at Savannah River. The map on Figure 2 shows the boundaries of the ID site. The SRID site is actually a small part of a larger surrounding remediation site with an existing pump and treat system in place. As such, the ISBR demonstration at the SRID was set up to address a "hot spot" of this overall larger contaminant plume. Adapting from Hazen 1992, the test plan gives us the following description of the test site and the history behind the contamination problem:

> The Savannah River Site is a 300 square mile facility owned by the U.S. Department of Energy and operated under contract DE-AC0989R18003S by the Westinghouse Savannah River Company. The site has been operated as a nuclear production facility for DOE since 1950. Many contaminated environments at SRS have been identified including both surface water and soils, subsurface sediment and groundwater. Cleanup of these wastes and waste sites has become a top priority for DOE. The 300-M Area operations of SRS were used to fabricate fuel and target elements that were later irradiated in SRS reactors. During these operations the elements are degreased at several stages in the process. These degreasing operation generated large amounts of metal-degreasing solvent wastes. From 1952 to 1982, M Area used an estimated 13 million pounds of chlorinated degreasing solvents (Marine and Bledsoe, 1984). Evaporation alone accounted for 50 to 95% loss, while the remainder went to the M Area process sewer system. Marine and Bledsoe (1984) estimate that as much as 2 million pounds may have been released to the sewer that leads to the M Area Settling Basin; another 1.5 million pounds went directly to the A14 outfall at Tims Branch. The discharges to the M Area Settling Basin consisted primarily of trichloroethylene (TCE: 317.000 lb.), tetrachloroethylene (PCE: 1,800,000 lb.), and 1,1,1 -trichloroethane (TCA: 19,000 Lb.) (Marine and Bledsoe, 1984). Solvents were detected in the groundwater below M Area Basin in 1981 and visual inspection of the terra cotta pipe of the process sewer line revealed cracks and root penetrations; this pipe was relined in 1984. The solvents discharged into the settling basin spread through the vadose zone and entered the groundwater below the basin. The leaking process sewer line used to convey these wastes to the basin also released large quantities of the solvents into the surrounding vadose zone sediments. The process sewer line was abandoned and removed in 1986. The seepage basin was contained via a clay cap closure (RCRA) completed in 1991 (DPSPU 84-

## Integrated Demonstration Site at Savannah River

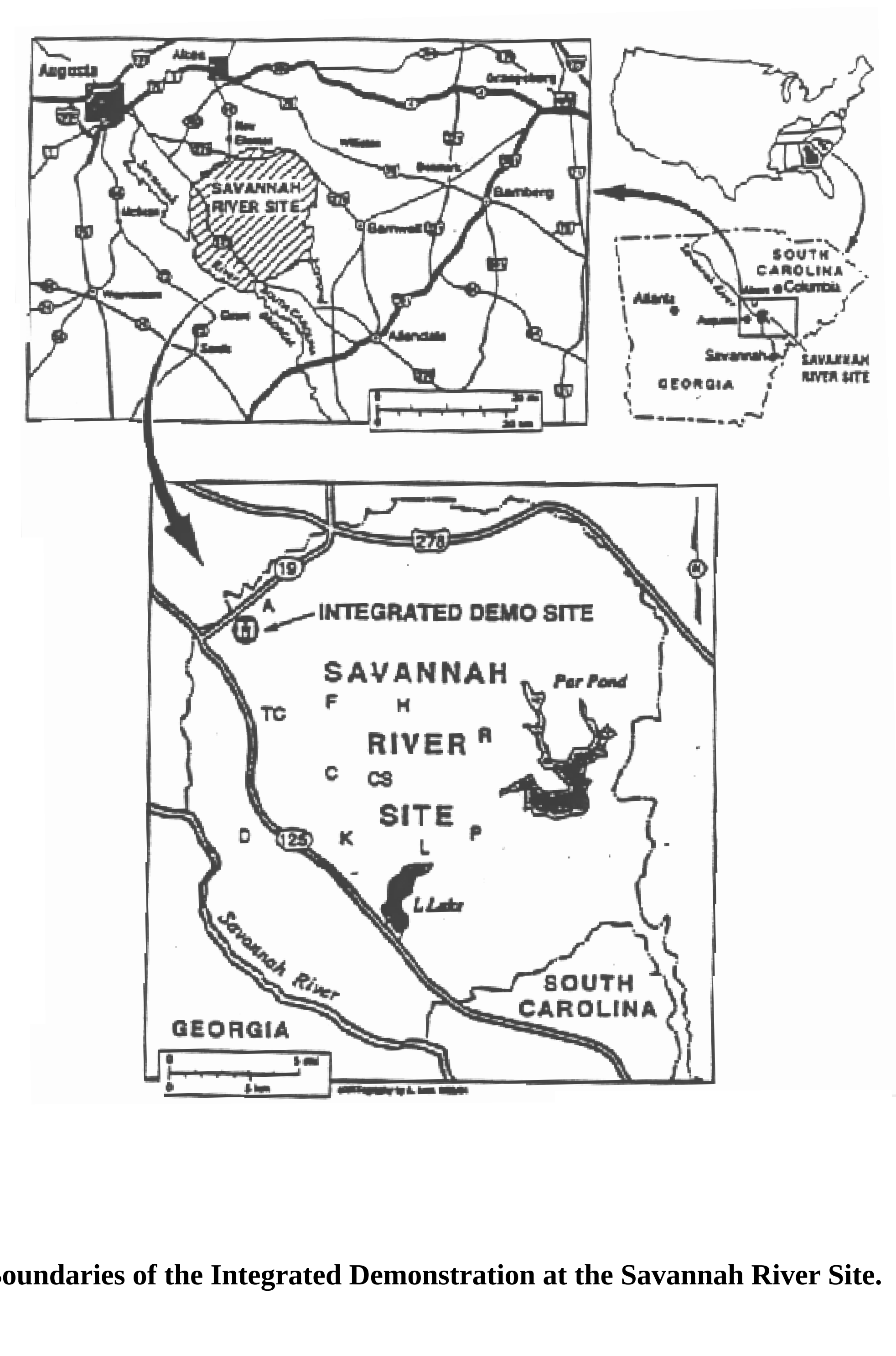



**Figure 2: Boundaries of the Integrated Demonstration at the Savannah River Site.**

> 11-11), State accepted and closed 9/91. Groundwater and sediment contamination in M Area is extensive; however, vadose zone (surface to water table) contamination is confined to the linear source associated with the leaking process sewer line, solvent storage tank area, settling basin, and the A-14 outfall. The residual solvents in the vadose zone associated with the abandoned process sewer line and the settling basin continue to leach into the groundwater covering more than 1 square mile. Since the plume caused by the leaking process sewer line was linear, horizontal wells were selected as the injection and extraction system that would best remediate the site. The horizontal wells were installed in 1988 (Kaback et al., 1989), and the area has been extensively characterized in terms of its hydrology, geology and ecology [Hazen 92].

The characterization data of the SRID site are given in Eddy [1991]. This study provides baseline information on the geology, geochemistry, hydrology, and microbiology of the demonstration site prior to the test. Some of the highlights of this report are summarized in the following:

> The sediments at the ID site are composed of layers of sand, clay and gravel. The hydrology of the subsurface is characterized by an approximately 130 foot thick vadose zone, a relatively thin water table, an underlying semiconfined zone, and a deeper confined aquifer. The clay layers are generally relatively thin or discontinuous with the exception of clay layers at an approximate depth of 160 feet and a thicker zone of interbedded clay and sand found at an approximate depth of 90 feet. The water table is an an approximate depth of 130 feet Concentrations of VOCs in the groundwater and sediments vary vertically and horizontally beneath the site: concentrations measured in groundwater collected from wells before the test (pre-1990) varied from approximately 400 to 1800 ppb (parts per billion) TCE and 20 to less than 200 ppb PCE.[3] Three dimensional data visualization shows that most of the contamination in the vadose zone at the site is associated with the clay zones at a depth greater than 90 feet below the surface.

### 3.2 Horizontal Wells

A major component of the ISBR demonstration was the use of horizontal wells with the goal of improving access to the subsurface. The demonstration site was selected along an abandoned process sewer line that carried wastes to a seepage basin operated at the Savannah River Site between 1958 and 1985. The sewer line acted as a source of contamination—it is known to have leaked at numerous locations along its length [Eddy 91]. Because the source of contamination was linear at this particular location within the overall plume, horizontal wells were selected for the injection and extraction system [Kaback 89].

Two horizontal wells were installed at the SRID site by Eastman Christensen, Inc., for the *In Situ* Air

Stripping Demonstration conducted in 1990. The lower horizontal well (used for air injection) is approximately 300 feet long and 165 feet below the surface. Recall that the water table is at approximately 130 feet in depth. The upper horizontal well (used for air extraction) is approximately 175 feet long and 75 feet below the surface. Figure 3 shows a cross sectional view of the location of the two horizontal wells at the SRID site.

## 4. Choice of Baseline Technologies

Because ISBR remediates both the vadose zone and the saturated zone, two conventional technologies were needed as the baseline for comparison.

> (1) Soil vapor extraction using vertical wells is the baseline technology for the remediation of the vadose zone.
>
> (2) Pump and treat using vertical wells is the baseline technology for the remediation of the saturated zone.

In combination, both of the conventional technologies served to remediate the test area in question and are considered common practice in current remediation efforts [EPA March 90, February 91]. It is important to note that we do not suggest that these two technologies achieve the exact same performance or effects as ISBR with horizontal wells; rather we are looking for a reasonably close set of conventional technologies that address the same overall contamination problem as ISBR. Besides being established technologies and widely in use, pump and treat/soil vapor extraction had other aspects which we could take advantage of for this report. Both technologies are used at the Savannah River Site; therefore, data exist which are relevant to the same hydrological and geological conditions as the ID site. A full scale, 600 gallon per minute (gpm), pump and treat groundwater remediation has been ongoing at the Savannah River Site A/M area since 1984 [Horvath 91]. A pilot scale study of soil vapor extraction with vertical wells was conducted at the ID site in 1987 [Looney 91]. These studies provided valuable data for a cost-effectiveness study on *in situ* air stripping done by Schroeder in 1992. Due to possible problems with the data in regards to the age and location of the tests in question, we chose not to use the data from both systems for this study. Instead, we assume the same extraction rate for the baseline technologies as occurred during the ISBR test. A complete discussion of the performance scenario can be found in Section 5.2. Several other remediation technologies exist which could possibly serve as baseline technologies, but for reasons discussed below these were not selected:

# Cross Sectional View of the ISBR Demonstration

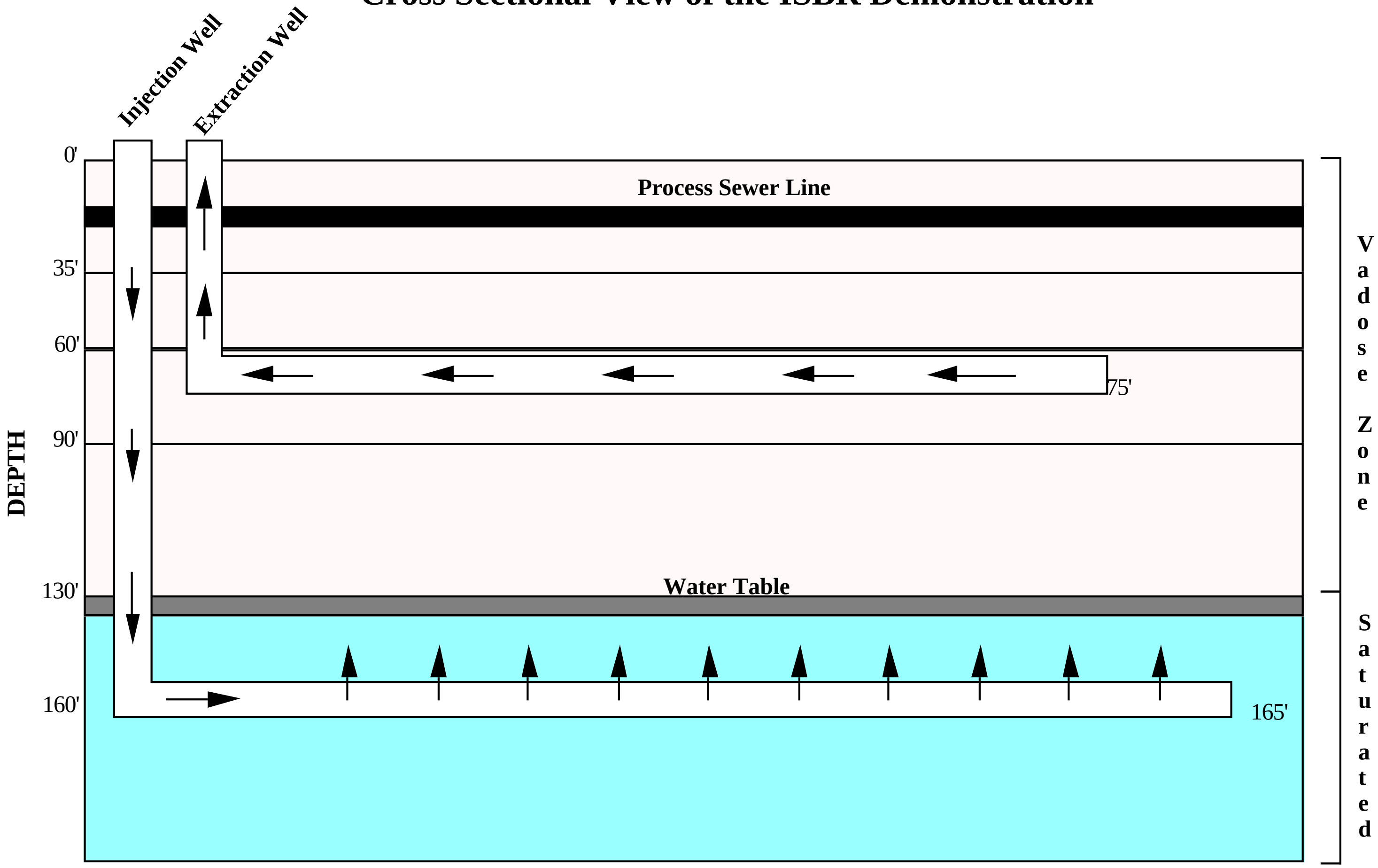



**Figure 3:** This figure shows the approximate locations of the horizontal wells used in ISBR in relation to the contamination source (process sewer line).

- Pump and Treat

  Pump and treat, by itself, is not a reasonable choice for the baseline technology. Contaminated soils in the vadose zone serve as a continuing source for contamination of the underlying groundwater. In practice, once contaminants have been found in the vadose zone, the vadose zone must be remediated.

- Excavation

  Given the depth (majority of the contamination occurs in the area below 90 feet deep) and extent (over one square mile for the VOC plume in the A/M area) of contamination at the Savannah River Site, this is not a reasonable alternative.

- In Situ Air Stripping with Vertical Wells

  A few examples exist in the literature of in situ air stripping with vertical wells: a vertical well extending below the water table is used for air injection, and a vertical well in the vadose zone is used for vapor extraction [Angell 91, Marley 92]. Various numbers and geometries of wells are proposed. Because this technology is relatively new, and not considered conventional or widely practiced, we did not consider it for the baseline case in this study.

- In Situ Air Stripping with Horizontal Wells

  In the past, this technology has shown that it can remediate the given contamination problems outlined in this report. This technology was demonstrated in the second half of 1990 at the SRID. The report, entitled, *In Situ Air Stripping: Cost Effectiveness of a Remediation Technology Field Tested at the Savannah River Integrated Demonstration Site* [Schroeder 92] analyzes the data obtained from that demonstration.

# 5. Performance Comparison

## 5.1. Elements of the Bioremediation Process

This section discusses various elements of the bioremediation process that were considered in the development of the performance scenario. Because TCE is the principle contaminant at the SRID, an understanding of its characteristics is necessary in order to understand performance. Although methanotrophic bioremediation is the main biological process being stimulated at the SRID, other bioremediation pathways are occurring simultaneously.

### 5.1.1 TCE Contamination

Trichloroethylene (TCE) may be the number one hazardous waste in the United States (see Table 1). It is known to be the most prevalent compound in Superfund sites [Keeler 91]. TCE was once extensively used as an industrial degreaser and solvent. TCE in groundwater has led to the closing of water supply wells in Massachusetts and New York. One study found TCE in 20% of 315 wells sampled in New Jersey [Russell 91].

Waste water and municipal water supply treatment systems do not reduce TCE concentrations to non-hazardous levels if they rely on coagulation, sedimentation, precipitative softening, filtration, and chlorination [Russell 91]. Other methods are required to deal with TCE.

Because TCE is chlorinated, it is difficult to degrade and has consequently accumulated in the environment over the years. The U.S. Environmental Protection Agency (EPA) has classified TCE as a priority pollutant on the basis of its widespread presence, suspected carcinogenity, and the fact that it can degrade into vinyl chloride which is known to be tumorogenic.

TCE in and of itself is not carcinogenic. Processing by the human liver confers a suspected carcinogenic nature. However, reductive dehalogenation through natural or induced means may produce vinyl chloride, which is known to cause cancer [Russell 91].

**Table 1. Properties of TCE**

| | |
|---|---|
| Density | 1.46 g/ml |
| solubility | 1100 mg/l |
| Koc | 2.42 |
| Henry's Law Constant | 0.00892 atm-$m^3$/mol@20°C |
| Molecular Weight | 131.4 |
| Boiling Point | 86.7° C |
| SDWA Maximum Contaminant Level | $5.0 \times 10^{-3}$ (mg/l) |

TCE is heavier than water, with a density of 1.46 g/ml. A large spill will tend to migrate downward and may pool when it reaches a low permeability layer. These pools of dense non aqueous phase liquid (DNAPL) are very difficult to locate and remediate. DNAPLs such as TCE can serve to contaminate large volumes of ground water as the water flows by. At the Safe Drinking Water Act contaminant level of $5.0 \times 10^{-3}$ mg/l, 1 kilogram of TCE can contaminate 200,000 cubic meters of water. That is equivalent to a cube of water over 58 meters per side.
TCE has a low Koc value and SRID sediments have little natural organic matter, meaning that there is little retardation of TCE transport in groundwater. At a Koc value of 2, TCE would migrate at one half of the speed of water. This relatively fast migration makes pump and treat technologies an attractive solution for aqueous TCE contamination; although the historical performance of pump and treat over the long-term is questionable due to the limitations of mass transfer and contaminant transport.

The Henry's Law constant for TCE is 0.00892, which makes for efficient transfer of TCE to the atmosphere (low solubility and high vapor pressure are also factors here). Schroeder 92 determined that air stripping can be a very cost effective means of remediation; however, use of an off-gas treatment system must be implemented under the guidelines of the current environmental regulatory climate.

### 5.1.2 Cometabolism and Methanotrophic Degradation

Cometabolism is a process where microorganisms growing on one compound, called the substrate, produce an enzyme which transforms another compound [Semprini 90]. In our case, indigenous organisms are growing on a substrate of injected methane, and producing an enzyme that breaks down TCE, on which the organisms cannot grow. The enzyme methane monooxygenase produced by methanotrophic bacteria growing on a substrate of methane will degrade TCE [Russell 91]. Methane monooxygenase is an extremely powerful oxidizer, thereby giving it the ability to oxidize a wide variety of normally recalcitrant compounds, including TCE. The resulting compound is an extremely unstable TCE-epoxide and it quickly hydrolyzes into various end products like carbon dioxide and chloride salts [Hazen 92].

### 5.1.3 Anaerobic Degradation

TCE is a highly oxidized compound; therefore, degradation is most likely to occur under reducing conditions. The first report of reductive dehalogenation was by obligate anaerobic methanogenic bacteria [Russell 91]. In theory, methanogenic consortia can convert TCE to harmless end products under anaerobic conditions in the presence of other oxidizable substrates and proper nutrients. However, if oxidizable substrates are lacking, a buildup of dichloroethylene (DCE) or vinyl chloride (VC) may occur. The advantage of anaerobic degradation is that there is no need to inject oxygen into the subsurface.

### 5.1.4 Aerobic Degradation

Although TCE is oxidized, it has been shown that several monooxygenases produced under aerobic conditions will degrade it. Complete mineralization is possible, and under aerobic conditions there is no build up of vinyl chloride.

**Checklist for Bioremediation**[4]

> *Site Assessment.* Accurate assessments must be made of the soil and the contaminants in the site. It is critical to determine the presence of any microbial inhibitors in the site.
>
> *Microorganism Assessment.* It must be determined whether organisms are present that will degrade the contaminant(s), and what their numbers are. It may be necessary to consider introducing organisms to the site.
>
> *Nutrients.* What are the levels of nutrients in the soil and contaminants? Will an additional carbon source or oxidizing agent be needed? The nutrient mix must be designed to stimulate the organisms to degrade the contaminants. Nitrogen and phosphorus may be needed, along with micro-nutrients such as molybdenum and nickel in some systems.
>
> *Reducing Agent.* The type of microorganisms will determine the electron acceptor (oxygen, nitrate, sulfate, carbon dioxide or organic compounds).
>
> *Adequate Mixing.* Mixing of organisms and the contaminated matrix must be provided for.
>
> *Other Parameters.* The temperature, pH, concentration, ionic strength, salinity, and presence of multiple pollutants can also be of importance.

## 5.2 Basic Form of the Performance Scenario

### 5.2.1 ISBR Performance Data

In this section, we construct a performance scenario in which Plan 1, based on the new ISBR technology as demonstrated at the SRID, is compared with Plan 2, based on “equivalent” conventional technologies. Here, we choose to construct Plan 2 so that it remediates the site conditions identical to those treated by ISBR at the SRID. In order to be fair to both technologies we will force equal physical system performance from both Plan 1 and 2. Both plans will be equal with respect to flow and overall capacity to handle a specific quantity of contaminants. The basis of the overall comparison is the sensitivity of the two plans in regards to what it costs to operate them over equal periods of time.

We must stress in advance that this approach is limited. Additional study is suggested to aid in applying gathered information to further work at SRS and/or to remediation efforts at other sites. We base this study on field performance data from the SRID site for the ISBR demonstration. The difficulty lies in making extrapolations from short-term field scale tests (e.g., 384 days) to performance over several years or more. As such, we first present results based on field data only.

We begin by describing the two plans used in this performance comparison. Plan 1 is based on the actual field demonstration of the new ISBR technology at the SRID which ran for a total of 429 days, operational for 90% of the time, yielding an actual run time of 384 days. The run lasted from March 1992 to May 1993. Of the 1,097 hours of down-time, 344 hours were due to power outages, 258 hours for electrical repairs, 120 hours for experiments, 285 hours for maintenance and 90 hours due to inclement weather. For the sake of simplicity, we assume that an equal amount of run time is necessary for both technologies.

The test site was the same area used for the In Situ Air Stripping (ISAS) test run during the second half of 1990. It should be noted that while ISAS and ISBR are based on the same physical principles, they are not the same technology. Any additional equipment needed to add methane and nutrients to ISBR was incorporated into the original ISAS system, thereby creating a new system and allowing for the biological component that adds to the overall remediation of the site. The ISBR system was also smaller than the in situ air stripping system due to the lower flow rate used by ISBR compared to ISAS. All equipment costs were upgraded to reflect current prices. Differences in initial site concentrations and flow rates between the ISAS and ISBR demonstration play a direct role in the overall cost of the remediation. Under the ISAS demonstration, the original system was designed to remove volatile organic contaminants (mainly TCE and PCE) from soils and sediments above and below the water table as well as groundwater, and the contaminants were released *untreated* into the air. Stricter air quality standards have eliminated this option. To handle the volatilized gas from the extraction process, a catalytic-oxidation (cat-ox) off-gas system was added to destroy any contaminants which were extracted.

The ISBR system uses two horizontal wells. The first well is an injection well, 300 ft long and 165 ft deep (about 35 ft below the water table). The second well is an extraction well, 175 ft long and 75 ft below the surface (in the vadose zone). Air was injected into the deeper well at an average rate of 208 standard cubic feet per minute (scfm). If an injected/extracted process using only air was employed, the physical process of air stripping would take place (although in order to be cost effective, a higher rate of injection and extraction would be necessary). By blending a concentration of methane (between 1% and 4%) and any necessary chemical nutrients (nitrogen in the form of nitrous oxide, and phosphorus in the form of triethyl phosphate), a biological element for remediation as well as the physical component is provided.

The methane provides the necessary material substrate for the indigenous microorganism to produce the enzyme methane monooxygenase which, in turn, degrades the TCE. The chemical additives necessary for production of methane monooxygenase were injected into the site in gaseous form, thereby eliminating the need for a delivery medium such as deionized water in which to dissolve the chemicals. This process has the added advantage that the gases, nitrous oxide and triethyl phosphate, can disperse more easily in the subsurface, allowing for greater distribution among the in situ microorganisms. Air was extracted from the shallow well at an average rate of 254 scfm for 384 days. A catalytic-oxidation off-gas system operating at 900˚F and 300 scfm was used in the ISBR demonstration to destroy the extracted VOCs. The 12,096 pounds of VOCs removed are a direct measure of the physical (vacuum) component of ISBR. Figure 4 shows the amount of VOCs removed over time via the vacuum component. These numbers were measured from the extracted air stream during the ISBR demonstration. Numerical modeling of the subsurface conditions at the SRID have been conducted by the Earth and Environmental Science Division at Los Alamos National Laboratory. The computer model takes into account such detailed factors as hydrology, geology, geochemistry and subsurface tomography to determine what actually took place in the subsurface during the ISBR run. Modeling results show that the biological component of ISBR destroyed an additional 41% of VOCs above the vacuum component [Travis 94]. Post-characterization studies conducted at the SRID on soil sediments show that an additional 43% of VOCs have been destroyed via the biological process. It is important to note that the data collected during the ISBR run was reviewed by a consensus of the Bioremediation Technical Support Group (Expert Panel). This group of experts from DOE, USGS, EPA, industry, and academia met on a regular basis for the last 3 years and provided unique and valuable insights for the planning, execution and evaluation of this demonstration. This group is responsible for the success of this demonstration which is the largest and most technically comprehensive full-scale in situ bioremediation demonstration ever performed [Hazen 94]. The concurrence of these independent sources as to the amount of bioremediation occurring strongly supports the conclusion that the biological component of ISBR did indeed destroy a significant amount of contamination. For purposes of this study we will round the percentage remediated due to bioremediation to 40% and use this estimate in our cost-effectiveness analysis. In Section 7, we examine the impact of changes in the biological component on cost per pound remediated.

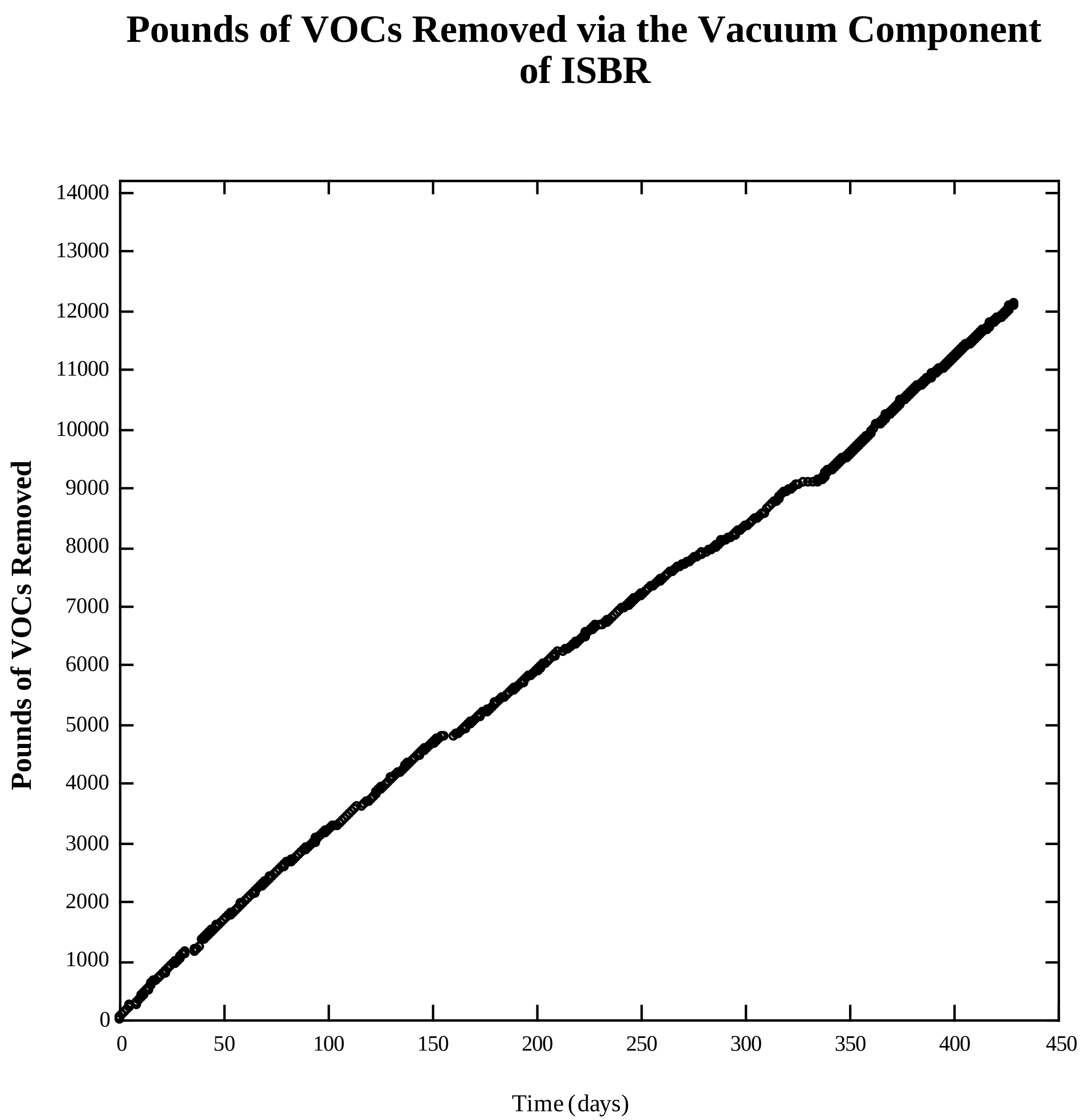



**Figure 4:** Total pounds of VOCs removed via the vacuum component of ISBR during the test run. The 12,096 pounds of VOCs removed is the baseline vacuum extraction performance used in all subsequent economic calculations.

### 5.2.2 Baseline Performance Data

Next, we consider Plan 2. We have engineer designed the pump and treat/soil vapor extraction system to perform optimally. It is integrated to avoid overlapping of equipment and materials, and is located in an area exactly the same as the ISBR demonstration in regards to all necessary site characteristics, including overall concentration of contaminants. This caveat is necessary due to the nature of the short-term field data available from the SRID site. All available field data at the SRS on both pump and treat and soil vapor extraction were for a much shorter duration than the 384 days used by ISBR. While data exist for both soil vapor extraction and pump and treat, it was felt by all investigators that the data were unreliable due to age and duration.

The physical, kinetic laws which dictate contaminant transport were another reason for using this caveat. Pump and treat, as well as soil vapor extraction, are governed by these mass transfer processes and the initial site concentration plays a direct role in the outcome of any remediation effort. The vacuum component of ISBR is also based on the mass transfer process, and therefore laws of contaminant transport apply as well. Because all three technologies can be greatly affected by the total concentration levels, the only way to make a fair comparison is to assume an equal level of concentration. With the actual field data for the pump and treat system at the SRS a fair comparison was not possible.

In fact, the closest pump and treat well to the ISBR site is the RWM-1 well, located 100 feet away, in an area of much higher contamination. The concentration of contaminants in the area of the ISBR demonstration is 2,000 ppb (2,000 x $10^{-6}$ g/l) whereas the concentration in the RWM-1 area is 50,000 ppb (50,000 x $10^{-6}$ g/l) [Looney, June 91]. Thus, the concentration of the closest pump and treat well is 25 times higher than the concentration where ISBR was demonstrated. Because the baseline system is designed to handle the high contaminant concentration, its costs will be unfairly high if that system were applied to the low concentration of the ISBR site. By assuming that both systems, ISBR and the pump and treat/soil vapor extraction, can handle equal flow and have equal performance levels, we successfully remove the bias against the baseline system and create a level playing field on which to analyze the technologies.

It is for these reasons we have assumed equal concentration and physical performance for both Plan 1 and Plan 2. We assume both systems are located in equal areas of equal concentration and that the physical variables of contaminant transport will remove the same amount of VOCs given equal time. As stated previously, the biological component adds 40% to ISBR's physical performance.

Now that the field for comparison has been established, the scenario can be developed. To remediate a region of groundwater at a site that is approximately 300 ft long by 60 ft wide by 35 ft deep, we use 1 groundwater pumping well 175 ft deep and screened 35 ft at the bottom [Savannah River Plant 86; Horvath 91].

To remediate a region of vadose zone at a site that is approximately 175 ft long by 150 ft wide by 100 ft deep, we use 4 vertical soil vapor extraction wells. Field data, available from a pilot study of vertical vacuum wells in the A/M area at the SRS, suggest that one of the wells screened over 100 ft of the vadose zone has a radius of influence of at least 75 ft [Looney, August 91].

For the purpose of this performance scenario, the four vertical SVE extraction wells used in the baseline system equal the one horizontal extraction well of ISBR. In Section 6.2 we vary this number of SVE wells to examine the cost sensitivity. One of the main selling points of the current horizontal wells used at the SRID is their ability to allow for greater contact between the contamination plume and the air stream of the remediation technology being tested. The SVE system has a total of 300 scfm for all four wells which is roughly equal to the extraction rate used by the ISBR system. Pump and treat is based on one well pumping at 30 gpm. The pumped effluent is released to an air stripping tower with a capacity of 30 gpm and 200 scfm. Volatilized contaminants are sent to a catalytic-oxidation off-gas system where they are destroyed along with the contaminants captured by the soil vapor extraction system. The total performance of the off-gas system is 500 scfm (300 scfm from SVE and 200 from pump and treat) operating at 900˚F.

We will assume that our combined baseline system will remediate the same amount of VOCs in an equal amount of time (12,096 lbs of VOCs in 384 days) as the vacuum component of ISBR. It should be noted that we are favoring the baseline technologies with this assumption. Based on actual SVE data extrapolated from the 1987 pilot study (approximately 7,600 lbs VOCs removed in 384 days) and the pump and treat data from a 30 gpm system pumping on a 2,000 ppb site (approximately 277 lbs VOCs removed in 384 days), Plan 2 would only remediate 7,877 pounds of VOCs. Clearly our assumption is in favor of the established technology by giving it a greater performance for an equal amount of time. Table 2 gives a overview of Plans 1 and 2.

**Table 2. Implementation Details of Plan 1 and Plan 2. (Note: Plan 2 is designed as an integrated system to avoid overlap of equipment and materials.)**

| | **Plan 1** | **Plan 2** | |
|---|---|---|---|
| **Technology** | In Situ Bioremediation | Soil Vapor Extraction | Pump and Treat |
| **Wells** | 1 horizontal injection well (300 ft long, 165 ft below the surface)<br><br>1 horizontal extraction well (175 ft long, 75 ft below the surface) | 4 vertical wells (130 ft deep, 100 ft screens) | 1 vertical well (175 ft deep, 35 ft screens) |
| **Vapor Extraction Rate** | 254 scfm (average) | 300 scfm maximum | (not applicable) |
| **Air Injection Rate** | 208 scfm (average) methane @ 1% - 4% | (not applicable) | (not applicable) |
| **Pumping Rate** | (not applicable) | (not applicable) | 30 gpm |
| **Contaminants Extracted at Surface** | 12,096 lbs (384 day test)<br><br>Average (384 day test): ~32 lbs per day (vacuum component only) | 12,096 lbs (384 day test)<br><br>(Total amount assumed to be equal to actual removed by ISBR during test run.)<br><br>Average (384 day test): ~32 lbs per day. | Included in soil vapor extraction |
| **Bioremediation** | 40% above vacuum component (4,838 lbs) | (not applicable) | (not applicable) |
| **Surface Treatment of Extracted Vapor or Groundwater** | catalytic-oxidation | catalytic-oxidation | air stripping tower and catalytic-oxidation<br>(clean effluent water from the air stripper released to permitted outfall) |

### 5.3 Comparison of In Situ Bioremediation with Baseline Technologies

In this section we highlight some of the differences in performance between ISBR and the baseline technologies (soil vapor extraction with pump and treat). For remediation of the vadose zone, both the physical component of ISBR and soil vapor extraction (SVE) employ essentially the same method. Contaminants are volatilized into a moving air stream and are transported to the surface through the extraction well. In the case of ISBR, air/methane is injected into the subsurface below the vadose zone. Extraction takes place in a vadose zone well. SVE is a more passive system in the sense that no air is injected into the subsurface. Air enters the vadose zone from the ground surface, and vapors are extracted through the SVE well.

For purposes of selecting a conventional technology that remediates the saturated zone, pump and treat is appropriate for our comparison. However, as a method for aquifer restoration, pump and treat is considered to have significant limitations [Mackay 89; Doty 91]. In the remainder of this section, we describe how the historical long-term performance of pump and treat systems influenced our choice of how to set up a performance comparison with ISBR.

Results of a recent analysis suggest that pump and treat is ineffective for permanently reducing levels of aquifer contamination to meet health-based goals for groundwater [Doty 91]:

> The ideal scenario would be a steady decrease in contaminant concentrations until the target level is attained. Performance records suggest, however, that although concentrations may drop initially, this decline is followed by a leveling of concentrations with little or no further decrease in concentrations. At sites where the plume appears to be well contained, concentrations have leveled after average VOC concentration reductions of approximately 60% to 90% in onsite wells, with large masses of contamination (approximately 50%) remaining in the aquifer. At all sites where contamination concentrations have leveled, the concentrations remain well above the target levels, even at sites where cleanup goals were established above drinking water standards.

The above behavior is due to contaminants in the saturated zone that are sorbed to aquifer material and act as slow, non-equilibrium, diffusion-limited, continuous sources for contamination of the groundwater [Roberts 91]. Because of kinetic limitations, residual saturation, and other subsurface sources such as dense non-aqueous phase liquids (DNAPLs), the rate of contaminant mass removal by pumping wells is exceedingly slow [Hall 88].

Given our inability to accurately predict performance over the long term, we will try to address the question of performance and cost by making several basic assumptions and applying these same conditions to both Plans 1 and 2. Economic comparisons will be made on short-term costs, relying on actual field data and using cost sensitivity analysis; while life-cycle costs will be estimated in relation to possible time to achieve cleanup.

# 6. Cost Effectiveness of ISBR as demonstrated at the SRID

## 6.1. Costs for Field Scale Test (Short-Term Duration)

The first economic comparison we will use is a calculation of the short-term costs in relation to performance. For ISBR, our analysis relies on the performance data obtained from actual short-term field tests to calculate a cost per pound of VOCs remediated. Data from pump and treat/soil vapor extraction are obtained by designing equal performances for both systems. We then use the field data obtained from the vacuum component of ISBR to also calculate a cost per pound of VOCs remediated, thereby giving us an equal comparison of the two plans being studied.

### 6.1.1 Amortization of Fixed Equipment

Tables 3 and 4 show the cost for the short-term, field-scale test for each of the technologies. The equipment capital costs shown in Tables 3 and 4 are amortized over the useful life of the equipment, which is assumed to be 10 years. Amortization is the process of paying back a loan with interest. By purchasing a bond for the equipment and paying it back over 10 years, the costs for the capital equipment are spread out over that period. All short-term equipment costs are amortized at 7%, which is assumed to be the interest on the loan. The loan is paid yearly and is extinguished in 10 years.

### 6.1.2 Cost for Methane Injection

One feature in our comparison of both plans that is unique to the ISBR demonstration is the use of methane to stimulate the indigenous microorganisms to bioremediate the TCE. In order for this process to take place, methane must be added into the injected air stream. The cost for methane injection comes under two categories in Table 3. There is the capital cost for the equipment necessary to inject the methane into the well, and the consumable cost for the methane itself.

## Table 3. Short-term Costs for In Situ Bioremediation

| | | |
|---|---|---|
| Duration (days): | 384 | |
| Lbs VOCs removed via vacuum component of ISBR | 12,096 | |
| Annual removal rate, vacuum only (Lbs VOCs) | 11,498 | |
| Total destroyed, including 40% biological addition (Lbs VOCs) | 16,934 | |
| | *Costs* | *Cost/Lb VOC* |
| *Site Costs* | | |
| Site costs (set up and level area) | $5,400 | |
| Subtotal: Site Costs | $5,400 | |
| Site Cost/Lb VOC Removed | | $0.32 |
| *Equipment Costs* | | |
| Design and engineering {2} | $19,200 | |
| Mobile equipment (pickup truck) | $18,000 | |
| Fixed equipment—Well installation (subcontracted) {1} | | |
| Air injection well (165 ft. deep, 300 ft. long) | $100,500 | |
| Air extraction well (75 ft. deep, 175 ft. long) | $82,500 | |
| Subtotal: Well installation | $183,000 | |
| Fixed Equipment—Other equipment | | |
| Air injection compressor system (260 cfm) | $18,700 | |
| Air extraction system (530 cfm blower) | $16,100 | |
| Vapor air separator (c/s 1 @ 260 cfm) | $1,700 | |
| Catalytic-oxidation off-gas treatment (900˚ F, 260 cfm) | $57,000 | |
| Methane Blending system | $37,500 | |
| Monitoring equipment | $18,000 | |
| Temporary storage (metal shed) | $1,600 | |
| Piping and insulation (10% of fixed other equipment cost) | $15,060 | |
| Electrical (12% of fixed other equipment cost) | $18,072 | |
| Subtotal: Other equipment | $183,732 | |
| Total Equipment Costs | $403,932 | |
| Amortization fixed charge rate | 0.70 | |
| Site Equipment Costs, one year | $57,511 | |
| Subtotal: Site Equipment Costs during test | $60,505 | |
| Equipment Cost/Lb VOC Removed | | $3.57 |
| *Labor Costs {2}* | | |
| Mobilize/demobilize (based on 200 hrs set up & tear down) | | |
| Technician — 2 | $24,800 | |
| Laborers — 2 | $23,200 | |
| Oversight engineer — 1 | $28,400 | |
| Per diem | $9,750 | |
| Monitoring/maintenance crew | | |
| Technician — 1 (384 days @ 2 hrs/day) | $47,616 | |
| Oversight engineer — 1 (384 days @ 0.5 hrs/day) | $27,264 | |
| Subtotal: Labor Costs | $161,030 | |
| Labor Cost/Lb VOC Removed | | $9.51 |
| *Consumable Costs {3}* | | |
| Catalytic material | $22,000 | |
| Electricity — 145 kW/HR (24 hours/day) | $66,816 | |
| Methane [(natural gas) 1,392,774 scf used by SRS] | $8,979 | |
| Lubricants | $768 | |
| Chemical additives | $13,440 | |
| Maintenance supplies | $15,360 | |
| Subtotal: Consumable Costs | $127,363 | |
| Consumable Cost/Lb VOC Removed | | $7.52 |
| TOTAL SITE COSTS | $354,298 | |
| TOTAL COST/LB VOC REMOVED (including biological addition) | | $20.92 |

Notes:
{1} Original estimate for wells taken from J. Schroeder memo of 3/24/92 and updated to December 1993 dollars.
{2} Labor rates per hour (industry averaged): Design engineer $80; Oversight engineer, $142; Technician, $62. Laborer, $58.
{3} Consumable supplies: Catalytic material (initial charge), $22,000; Electricity, $0.05/kWH; Chemicals, $35/day Methane @ $0.64469/100scf; Lubricants, $2/day; Maintenance supplies, $40/day

## Table 4.  Short-term Costs for Pump and Treat/Soil Vapor Extraction

| | | |
|---|---|---|
| Duration (days): | 384 | |
| Lbs VOCs removed:  (4 vertical SVE wells, 1 pump and treat well) | | 12,096 |
| Annual removal rate (Lbs VOCs) | 11,498 | |
| | *Costs* | *Cost/Lb VOC* |
| *Site Costs* | | |
| Site costs (set up and level area) | $7,500 | |
| Subtotal: Site Costs | $7,500 | |
| Site Cost/Lb VOC Removed | | $0.62 |
| *Equipment Costs* | | |
| Design and engineering {1} (400 mhrs) | $32,000 | |
| Mobile equipment (pickup truck) | $18,000 | |
| Fixed Equipment: Well installation (Pump and Treat) | | |
| Drill and case (1 x 175 ft. x 6" dia x $23.00/lf) | | $4,020 |
| Screens (1 x 6" dia SS @ 35 ft/well x $13.00/lf) | | $460 |
| Sampling (35 samples @ $250 each) | $8,750 | |
| Seals (1 @ 10 sy x $4.00 sy) | $40 | |
| Gravel pack (2.3 cy @ $25/cy) | $60 | |
| Subtotal: Well installation (Pump and Treat) | $13,330 | |
| Fixed Equipment: Well Installation (Soil Vapor Extraction) | | |
| Drill and case (4 x 130' x 4" DIA @ $15/lf) | $7,800 | |
| Screens (4 x 4" DIA PVC x 100' well @ $8/lf) | | $3,200 |
| Sampling (104 samples @ $250 each) | $26,000 | |
| Seals (4 x 10 sy @ $4/sy) | $160 | |
| Gravel Pack (8 cy @ $25/cy) | $200 | |
| Subtotal: Well installation (Soil Vapor Extraction) | | $37,360 |
| Fixed Equipment: Other equipment | | |
| Pump (30 gpm, submerged) | $3,750 | |
| Air stripping tower (30 gpm, 200 cfm, 20" dia) | | $9,150 |
| Cleaning package, control panel, fan | $7,500 | |
| Vapor air separator (1 @ 300 cfm) | $2,000 | |
| Manifold system (4" PVC with valves) | $3,000 | |
| Vapor Extraction Unit (300 scfm) | $13,500 | |
| Catalytic oxidation off-gas treatment (900˚F, 500 SCFM) | $76,000 | |
| Test/monitor weir | $3,750 | |
| Monitoring equipment | $18,000 | |
| Temporary storage (metal shed) | $1,600 | |
| Piping and insulation (10% of fixed other equipment cost) | $13,825 | |
| Electrical (12% of fixed other equipment cost) | | $16,590 |
| Subtotal: Other equipment | $168,665 | |
| Total Equipment Costs | $269,355 | |
| Amortization fixed charge rate | 0.07 | |
| Site Equipment Costs, one year | $38,350 | |
| Subtotal: Site Equipment Costs during test | $40,346 | |
| Equipment Cost/Lb VOC Removed | | $3.34 |
| *Labor Costs {1}* | | |
| Mobilize/demobilize (based on 300 hrs set up & tear down) | | |
| Technician — 2 | $37,200 | |
| Laborers — 2 | $34,800 | |
| Oversight engineer — 1 | $42,600 | |
| Per diem | $14,625 | |
| Monitoring/maintenance crew | | |
| Technician — 1   (384 days @ 2 hrs/day) | $47,616 | |
| Oversight engineer — 1   (384 days @ 0.5  hrs/days) | $27,264 | |
| Subtotal: Labor Costs | $204,105 | |
| Labor Cost/Lb VOC Removed | | $16.87 |
| *Consumable Costs {2}* | | |
| Catalytic material | $27,500 | |
| Electricity — 175 kW/HR (24 hrs/day) | $80,640 | |
| Lubricants | $1,152 | |

**Table 4. Short-term Costs for Pump and Treat/Soil Vapor Extraction continued**

| | | |
|---|---|---|
| Maintenance supplies | $19,200 | |
| Subtotal: Consumable Costs | $128,492 | |
| Consumable Cost/Lb VOC Removed | | $10.62 |
| TOTAL SITE COSTS | $380,443 | |
| TOTAL COST/LB VOC REMOVED | | $31.45 |

Notes:
{1} Labor rates per hour (industry averaged): Oversight engineer, $142; Technician, $62; Laborer, $58; Design engineer, $80
{2} Consumable supplies: Catalytic material (initial charge), $27,500; Electricity, $0.05/kWH; Lubricants, $3/day; Maintenance supplies, $50/day.

In addition to the compressors, blowers, piping and electrical components necessary for in situ bioremediation with horizontal wells, there is the additional cost of the methane blending system to incorporate the natural gas into the air stream. The $37,500 methane blending system figured into the total equipment cost of the system is compatible with the rest of the equipment to deliver the proper concentration of methane given the system capacity for which it is designed. Although the total system design itself is very similar to the one used for the ISAS demonstration, the equipment size has been down-scaled to account for the lower flow rate which is used in ISBR.

One of the advantages of the ISBR system is how it injects methane into the ground. The system is designed to utilize natural gas which is readily available, as well as requiring a minimum amount of additional equipment. The cost is also substantially less than the other available alternative of technical-grade methane (99% pure) which at the industry average cost of $0.21 per cubic foot would raise the price of the methane alone to $292,483. The ISBR demonstration used 1,392,774 standard cubic feet (scf) of methane at a cost of $0.64469/100 scf, giving a final cost for the methane of about $9,000. This price is the standard contract rate from South Carolina Gas and Electric. This design feature of the ISBR demonstration is a cost savings of over 3,000% with respect to the consumable cost of methane.

If we add both the cost for the methane blending system and the cost of methane injected, the total is about $46,500 ($37,500 + $9,000 respectively). The $46,500 necessary to stimulate the biological component is only a 13% increase over the same system run only on air stripping (e.g. no addition due to stimulated bioremediation). It is only necessary for an additional 1,570 lbs of VOCs to be remediated via the biological component for the methane injection system to pay for itself (for a detailed description of the short-term costs of ISBR, refer to Section 6.1.4).

### 6.1.3 Cost for Off-Gas System (catalytic-oxidation)

The ISBR demonstration incorporated a catalytic-oxidation off-gas treatment system to destroy the extracted contaminants. Extracted air containing volatilized chlorinated hydrocarbons is passed through the treatment system and destroyed, leaving carbon dioxide and hydrochloric acid gas as the by-products. In addition to the capital cost of $57,000 for the cat-ox unit itself (operating temperature of 900˚ F at 300 scfm), there is also the consumable cost of $22,000 for the catalytic material. This cost is an initial cost to start the system. Used properly, the catalytic material will last approximately a year. It is possible to recharge the catalytic block provided fouling has not occurred. Since it is impossible to determine all the possible situations where fouling can occur and the cleaning of catalytic blocks is not standard industry practice at this time, we will assume a new catalytic block will need to be purchased each year of operation in any life-cycle analysis. Because cleaning of the block is possible, this is an area of potential savings which can be exploited in the future by all remediation technologies. For the ISBR run, the cat-ox system was 94% efficient, thereby releasing, at most, only 729 pounds of VOCs untreated into the air. The South Carolina air emissions standards allow for no more than 9.6 pounds of TCE and PCE to be released daily. According to the data received from the SRID, during the ISBR run there were no days when the release of untreated VOCs exceeded the air emissions standards.

In order to keep both plans equivalent in final performance, a catalytic-oxidation off-gas system was added to the integrated pump and treat/soil vapor extraction system. The off-gas system is designed to handle the contaminants from both the pump and treat as well as the soil vapor extraction system. The cost for equipment and catalytic material is higher than the equivalent equipment necessary for ISBR, but this is due to the higher flow rates which are being delivered by the combination of both remediation systems. Keeping this in mind, the off-gas system for the baseline technologies costs $76,000 (operating temperature: 900˚F at 500 scfm) in capital expense and $27,500 in catalytic material. We assumed that our baseline off-gas system had a destruction capability equal to the one designed for ISBR, and we used the cost for a new catalytic block in each year the life-cycle costs were calculated.

### Cat-Ox versus GAC

In Schroeder's report on the ISAS demonsration, a granulated activated charcoal (GAC) system was designed into the remediation system to handle any off-gas contaminants. To test the cost effectiveness of cat-ox versus GAC, we went back to the original ISAS report to determine how much the cost per pound of VOCs remediated changes if one incorporates a cat-ox system versus a GAC system using in situ air stripping. We updated the ISAS estimates by assuming the systems will run on line electric power and we brought all costs up to December 1993 dollars.

Using a cat-ox system, ISAS costs ≈ $14 per pound of VOCs removed. The cost of ISAS with GAC depends on the price of carbon recharge for the off-gas system. It takes 2.23 pound of carbon per pound of VOCs for a GAC system. This is roughly based on the ability of 1 pound of carbon to hold 0.5

pounds of VOCs. The cost per pound for carbon varies in different parts of the country, ranging from \$1.50 per pound at the Hanford Site [Grigsby 94] to \$3.00 per pound in other areas. At \$3.00 per pound of carbon, 16,000 pounds of VOCs removed via ISAS with GAC cost ≈ \$19 per pound of VOCs. That same amount removed with carbon at \$1.50 per pound drops the overall cost per pound removed to ≈ \$15 per pound of VOCs. Depending on what part of the country one is in, GAC costs between \$1 - \$5 per pound of VOCs removed more than cat-ox. For complete cost estimate tables regarding off-gas system costs, please refer to Appendix C.

Cat-ox has advantages, however, that are not necessarily reflected in the lower cost per pound remediated. It is simpler to operate since there is no need to swap out spent carbon and the contaminants are destroyed on-site, so there is no need to store and ship spent carbon. In a remote area, the cost associated with storage, transportation and swap time for GAC could drive the overall cost per pound much higher than the average cost of ≈ \$17 per pound VOC. Therefore, for the sake of overall convenience, catalytic-oxidation would seem to be the better off-gas choice for this remediation project.

#### 6.1.4 Overall Short Term Costs

Looking at total cost for all necessary equipment, labor, and consumable items gives a total short-term cost for the length of the demonstration. If we divide the total cost by the amount of VOCs remediated, it gives us a price per pound of VOCs remediated.

For ISBR we have a total cost of \$354,000 with a total of 16,934 (12,096 pounds removed via vacuum and 4,838 pounds destroyed via bioremediation) pounds of VOCs being removed by a combination of the vacuum and biological components, giving a cost per pound remediated of about \$21. This number is based on a 40% biological addition over what would be obtained by the vacuum component alone.

Plan 2 has a total cost of \$380,000. Assuming an equal vacuum performance of 12,096 pounds of VOCs removed (for description of Performance Scenario, see Section 5.2) gives a cost per pound remediated of about \$31.

A ratio of Plan 1 to Plan 2 costs shows that ISBR as demonstrated at the SRID is ≈ 32% more cost effective than the baseline system.

$$(\$31 - \$21)/\$31 \times 100 \approx 32\%$$

This is a considerable cost savings over the field run of the project. Where ISBR has the greatest potential as an effective new remediation technology is the possibility of an additional quantity of

VOCs destroyed via the biological component. Since the total cost of ISBR for the demonstration is at \$354,000, any amount of VOCs remediated via the biological component occurs at no additional cost, thereby lowering the cost per pound of VOCs remediated. It should be noted at this time that the two largest cost categories for both plans are the costs of consumables and labor (see Figure 5). This indicates that if one could shorten the operating time for a given remediation system, the overall cost for remediation should decrease.

### 6.1.5 Power Considerations

When designing a remediation system one must consider how to generate the power necessary for all the equipment. We have two possibilities: (1) to use line power, if available, or (2) to generate power via a diesel generator.

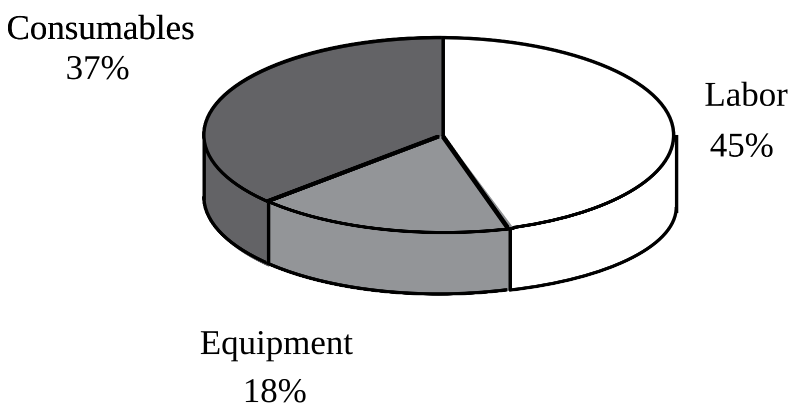
In all cost estimates in this report, we use line power to run the equipment. We have assumed that all power lines necessary to bring the electricity on-site are available and any hookups necessary are negligible in cost. In rural areas it may not be possible or cost effective to run the remediation system off line power due to the unavailability of electricity or the high cost of running lines to the site. In these situations, it will be necessary to generate the power via a diesel generator.

The capital equipment necessary for such an undertaking is minimal when compared to the overall cost of the system. For ISBR, the portable diesel generator (25 kVA), fuel storage tank, duct heater and all necessary wiring equipment and piping would cost about \$10,000. For Plan 2, the same equipment would cost \$13,000 (based on a 30 kVA generator). The major expense lies in the consumable costs of diesel fuel and the necessary lubricants for the generator.

With that in mind, the major power consuming components of ISBR are the compressor, blower, and the cat-ox system. Using field data obtained from the SRID during the ISBR run on actual energy usage, we know that ISBR uses 145 kWH (kilowatt hours) of electricity while the system is running. Energy prices are listed by various categories according to what the energy is used for, whether it is residential or industrial [Energy Information Administration 92]. At a cost of \$0.05/kWH, the cost to run line power is \$66,816 per year plus lubricant, at \$2/day (\$768.00 for the 384 day run), for a total of \$67,584. However if we need to run diesel power we will be consuming diesel at 10 gallons per hour (gph) and lubricants at \$75/day (the high lubricants cost is due to the nature of diesel generators which tend to burn oil/lubricants at a very high rate). Therefore, for the 384 day run ISBR would cost \$110,592 for diesel fuel (based on industry average price of \$1.20/gallon) and \$28,800 for lubricants, giving a total of \$139,752 over the run of the demonstration. This is a 52% increase in the consumable cost of

**Short-term Cost Category Breakdown for ISBR and the Pump and Treat/Soil Vapor Extraction Technologies**

## ISBR ($21/LB Remediated)




## PT/SVE ($31/LB Remediated)

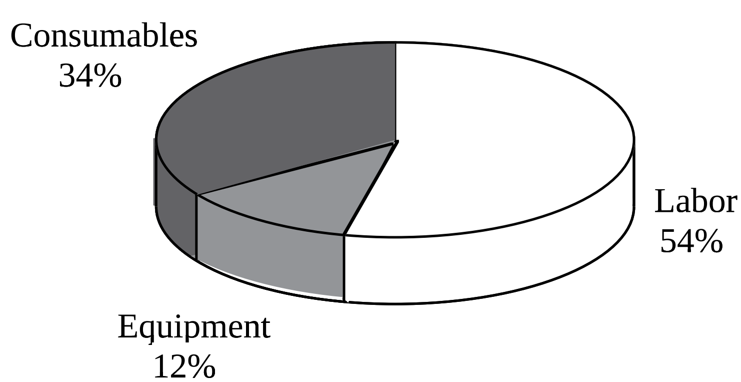



**Figure 5:** This figure shows the percentage of the total cost per pound of VOCs remediated in each cost category for both ISBR and the baseline Pump and Treat/Soil Vapor Extraction system. Note: Consumable and Labor Costs are approximately 85% of the total cost per pound of VOCs remediated for both technologies.

energy and lubricants over the electricity currently figured into our short-term cost estimates. This translates to an overall increase in the short-term cost of an additional $7.00 per pound VOC over the cost listed to run via line power. This increase is due solely to the choice of energy used.

Our integrated pump and treat/soil vapor extraction system uses 175 kWH of electricity at the same cost of $0.05 kWH. The cost to run the system on line power is $80,480 for electricity and $1,152.00 for lubricants (based on $3/day), which totals $81,632. This same system, running off diesel power would cost $132,710 for diesel fuel (based on 12 gph, diesel at $1.20/gallon) and $32,640 for lubricants (based on $85/day) for a total of $165,351. Again, this is a 52% increase in the consumable cost of energy and lubricants, raising the short-term cost from $31 to $38 per pound of VOCs remediated. Since consumable costs are incurred each day of operation, this increase will have to be incurred during the entire life of the project.

Therefore, it is definitely worth considering the power source that will be used to operate the remediation system. While the power choice that is made does not change the cost effectiveness of either technology, (ISBR is more cost effective than pump and treat/soil vapor extraction) the choice of using diesel power will increase <u>both</u> remediation efforts by an additional $7.00 per pound of VOC removed. It must be determined at what point the cost of running power lines to the site outweighs the overall consumable costs of operating via diesel power.

## 6.2 Cost Sensitivity of the Baseline Scenario to Number of SVE Wells

As mentioned earlier in the performance scenario (Section 5.2), one of the main selling points of ISBR with horizontal wells is that in cases where the contamination plume is along a linear source (as is the case at the SRID) a horizontal well allows for greater contact between the injected air stream and the contamination. The assumption is that the greater surface area of a horizontal well offsets the higher cost of horizontal well installation. In our analysis, we assumed that four vertical SVE wells were equal in performance to the one horizontal ISBR well. At the SRID, the cost for drilling the horizontal wells is ≈ $385 per foot . Compared with the ≈ $23 per foot to drill, case, screen, seal and pack vertical SVE wells, the argument could be made that by using more or fewer SVE wells with the same flow, one could lower the cost per pound remediated for the baseline system. Horizontal well drilling options are discussed in Section 6.3. Cost sensitivity, with respect to the number of SVE wells used by Plan 2, is examined here.

For the purpose of our analysis we will assume that regardless of the number of vertical SVE wells used, the same flow rate of 300 scfm will be distributed between them. The options we have chosen are 2, 3, 4, and 5 vertical SVE wells. Cost estimates were made using these possible combinations of number of wells combined with the 1 vertical pump and treat well. Where sampling was needed to monitor the process, the cost estimates were adjusted either up or down depending on the number of SVE wells used. The samples were figured at 26 samples per well at a cost of $250 dollars per sample. Table 5 shows the costs per pound of VOCs remediated for the different options of numbers of SVE wells used in Plan 2. Note that well drilling and the subsequent sampling for the SVE wells is a fixed expense and is therefore amortized over the ten year expected life of the equipment. Table 5 shows Plan 2 is not cost sensitive to the number of SVE wells being used. For detailed cost estimate tables regarding the number of SVE wells in Plan 2, please refer to Appendix A.

**Table 5. Cost Sensitivity of Number of Vertical SVE in Relation to Cost Per Pound Remediated (rounded to nearest dollar.)**

| Number of SVE Wells | Pre-amortized | Amortized Well | Cost Per Pound |
|---|---|---|---|
| 2 | $18,680 | $2,660 | $31 |
| 3 | $28,020 | $3,990 | $31 |
| 4 | $37,360 | $5,320 | $31 |
| 5 | $46,700 | $6,650 | $32 |

**6.3 Costs for Horizontal Wells**

As noted previously, the cost for installation of two horizontal wells (Plan 1) is much higher than the cost for installation of vertical wells (Plan 2). There are instances where the drilling of a horizontal well may be necessary regardless of the cost. For example, in some sites it may be necessary to drill under buildings or under a landfill containing hazardous material [Birdell 94]. Different drilling techniques for horizontal wells other than the short, 35 foot radius top-drive technique used by Eastman Christensen, Inc. at the Savannah River Site are described here. Some of these other horizontal drilling techniques can be expected to be far less expensive, particularly at shallower depths, than were required at the SRID site. Variables describing differences in directional drilling techniques include the following: radius of curvature, depth, coring, gravel packing, radials (multiple boreholes per well), and cost.

At this time, a 40 to 50 foot depth seems to indicate a critical distinction between drilling technologies for horizontal wells. At depths shallower than 40 to 50 feet, drilling technologies such as those used by the utility or cable industries may be applicable. These drilling methods apply cutting force with either a drill bit or fluids. Also, some push-type techniques are available where the drill stem is hydraulically forced into the earth, rather than being rotated or drilled. An advantage of push techniques is that they do not use drilling fluids or muds. Drilling fluids may circulate contaminants or may invade the subsurface formations, making it difficult to obtain good geologic samples or well development. Typically, these shallower techniques create holes with two open ends. That is, the drill bit begins at one end of the hole, traces a shallow arc, and emerges at the surface at the other end of the hole. Costs for these shallow methods may range as low as $50 per foot.

For depths greater than 40 to 50 feet, more expensive equipment is needed. One of these methods is the short radius top-drive system used by Eastman Christensen, Inc. for the two horizontal wells drilled for the ISAS demonstration. Other drilling methods include steerable mud-rotary motors. Most deeper drilling technologies put one hole in the ground and pull the casing along with the drill bit as the drilling proceeds, or casing is installed after the hole is drilled. When the horizontal total length is reached, the drill bit is pulled back out through the original opening. Costs for these deeper horizontal drilling methods range from ~$360 per foot for short radius top-drive systems[5] up to ~$700 per foot for some river channel crossing techniques [Schroeder 92]. While the deeper drilling methods have higher costs than the shallower methods, these costs are expected to decrease as companies gain more experience.

### 6.4 Cost of Baseline Technology Using only Soil Vapor Extraction

Recall from the performance description (Section 5.2) that we are using a soil vapor extraction system with 4 vertical SVE wells at a total flow of 300 scfm. Section 5.2 also explained how the concentration of VOCs in the test site area was 2,000 ppb and that at a pumping rate of 30 gpm, the pump and treat portion of our baseline technology would only remove 0.72 pounds of VOCs per day. In order to handle this problem we forced equal performance out of both systems, thereby giving an equal “playing field” on which to run the comparisons. In effect, we gave the baseline a higher performance than would have actually occurred if we did a field demonstration of the baseline system using the parameters of 300 scfm for SVE and pumping at 30 gpm.

In order to address the question of the relatively low return of pump and treat we have also estimated the cost of running soil vapor extraction alone. We assume a soil vapor extraction system with 4 vertical SVE wells operating at 300 scfm. VOCs removed are destroyed in a catalytic-oxidation offgas system operating at 900˚F. Assuming an equal performance of 12,096 pounds of VOCs removed over 384 days, the cost per pound of VOCs remediated is about $31 (for detailed cost estimates, please refer to Appendix A). At this price there would be no remediation of the saturated zone which is required by EPA if contamination is found in the vadose zone.

Why does the cost per pound remediated remain the same when we have removed one technology? Despite the actual low field performance of pump and treat, it is very inexpensive to operate in regards to equipment and labor. In addition, with the amortization of the capital equipment, the short-term costs essentially do not change if we remove the pump and treat system. For this reason it is worthwhile to keep the pump and treat system in our analyses and benefit from the additional remediation of the saturated zone.

## 6.5 Life-Cycle Costs

Our next analysis is a calculation of the life-cycle costs of both plans. Using present value we take into account the total operating cost of the baseline technologies for the project, including all necessary equipment, and assign a discount rate appropriate for the duration of the project. Data suggests that it would take somewhere on the order of 30 years via pump and treat to remediate the test site at the ID. If pump and treat/soil vapor extraction were used, that time would be cut to 10 years [Hazen 94]. Therefore, our five year estimate heavily favors the baseline technologies because we are ascribing a better performance over time than could be obtained in actual practice. It should also be noted that these baseline technologies could never achieve the Safe Drinking Water Act (SDWA) maximum level of contamination (5 - 7 ppb for TCE/PCE). ISBR, however, can remediate the site to these levels.

We use a real discount rate of 2.3% to calculate the present value [OMB March 94]. A real discount rate does not take into account any future inflation. The present value gives us an idea of how much the particular technology in question will cost in current dollars for the five years of operation. Life-cycle cost do not include post-closure monitoring of the site because these costs will be roughly the same for both plans and will be regulatory driven depending on the location of the remediation site and local law.

Once again, we are assuming pump and treat/soil vapor extraction has equal performance to ISBR without biological additions over the five years life-span of the project. The 11,500 lbs of VOCs destroyed in year one are the actual number of pounds of VOCs removed via vacuum extraction alone in the first year of the ISBR demonstration. The subsequent number of 8,625 pounds removed during year two is based on the assumption that as the overall concentration of the site decreases, the ability to pull out VOCs decreases as well. The 8,625 pounds is a decrease of 25% over the original 11,500 pounds removed in year one. For years three through five, we assume that the amount removed decreases by 50% from the year one amount, removing 5,750 pounds of VOCs per year. The 50% decrease which occurs in year three stabilizes and is assumed to remain constant for the duration of the run in years three through five. The total pounds of VOCs removed given the above assumptions equals 37,375 pounds over the five year period. The main question of concern is *"how fast can ISBR remediate the same amount of contaminants?"* ISBR can remediate the same site in roughly three years. It takes the pump and treat/soil vapor extraction system five years. This difference in time to remediate the site will play a role in the overall cost effectiveness of these technologies.

Tables 6 and 7 show the life-cycle costs for Plans 1 and 2 respectively. All capital equipment costs are incurred in year one and are <u>not</u> amortized. The other categories of consumables and operation/maintenance, with the exception of mobilization and demobilization, are incurred for all the necessary years of operation . The mobilization costs are incurred in year one when the set-up of the remediation technology occurs and the demobilization costs are incurred in the last year of opeartion, when the system is disassembled at the end of the project.

The life-cycle costs for Plan 1, which remediates the site in 3 years, are about $1 million or about $29 per pound of VOCs remediated. Plan 2, which remediated the same site in 5 years, costs about $1.4 million or about $38 per pound of VOCs remediated. Therefore, ISBR would save at least $400,000 at the SRID alone. This is a 25% savings over the comparable baseline technologies, while remediating the site two years faster.

As mentioned earlier, the baseline pump and treat/soil vapor extraction system would take on the order of 10 years to remediate the test site at the ID [Hazen 94, Looney June 91]. Given this information, Table 8 shows the life-cycle costs as figured to run the baseline system for 10 years. Remember that ISBR will remediate the site in 3 years and cost approximately $1 million. The baseline system will take 10 years and cost $2 million. ISBR, therefore, saves $1 million dollars and seven years time, a savings of 50%. It should be noted that even after the 10 years, pump and treat/soil vapor extraction still cannot clean up the site to the levels set forth by the Safe Drinking Water Act regarding maximum levels of contamination for TCE.

To summarize, ISBR can save between $400,000 to $1,000,000 at the SRID alone. If we assume that PT/SVE will take the estimated 10 years to clean the site to an acceptable level, then ISBR saves $1 million and seven years of remediation time. If we give the baseline technologies a performance that is <u>twice</u> its expected potential and clean the site to an acceptable level in 5 years, ISBR still saves $400,000 and two years clean up time at the SRID alone. Clearly, due to the widespread problem of VOC contamination which occurs in both the DOE complex and in the private sector, ISBR has a considerable potential to save a great deal of time and money if properly used.

## Table 6. Plan 1: In Situ Bioremediation Life-Cycle Costs (3 years)

| | Year 1 | Year 2 | Year 3 |
|---|---|---|---|
| VOC Extraction Rate + 40% Bio (lbs/yr.) | 16,100 | 12,075 | 8,050 |
| Capital Cost | | | |
| Site Cost | $5,400 | | |
| Equipment Cost | | | |
| Design and Engineering | $19,200 | | |
| Mobile Equipment | $18,000 | | |
| Well Installation | $183,000 | | |
| Other Fixed Equipment | $183,732 | | |
| Subtotal: Equipment Costs | $414,732 | | |
| Mobilization Costs (100 mhrs) | | | |
| Technicians (2) | $12,400 | | |
| Laborers (2) | $11,600 | | |
| Oversight Engineer (1) | $14,200 | | |
| Per Diem | $4,875 | | |
| Subtotal: Mobilization Costs | $43,075 | | |
| Operation and Maintenance Costs | | | |
| Monitoring /Maintenance | | | |
| Technician | $45,260 | $45,260 | $45,260 |
| Oversight Engineer | $25,915 | $25,915 | $25,915 |
| Subtotal: Monitoring/Maintenance Costs | $71,175 | $71,175 | $71,175 |
| Consumable Costs | | | |
| Catalytic Material | $22,000 | $22,000 | $22,000 |
| Electricity — 145 kW/HR ($0.05/kWH) | $63,510 | $63,510 | $63,510 |
| Methane (1,323,860 scfm/yr.) | $8,600 | $8,600 | $8,600 |
| Lubricants | $730 | $730 | $730 |
| Chemical Additives | $12,775 | $12,775 | $12,775 |
| Maintenance Supplies | $14,600 | $14,600 | $14,600 |
| Subtotal: Consumable Costs | $122,215 | $122,215 | $122,215 |
| Demobilization Costs (100 mhrs) | | | |
| Technician (2) | | | $12,400 |
| Laborers (2) | | | $11,600 |
| Oversight Engineer (1) | | | $14,200 |
| Per Diem | | | $4,875 |
| Subtotal: Demobilization Costs | | | $43,075 |
| TOTAL ANNUAL COSTS | $651,197 | $193,390 | $236,465 |
| TOTAL LIFE CYCLE PRESENT VALUE= (2.1% real discount rate) | $1,067,447 | | |
| PRESENT VALUE PER LB VOC DESTROYED | $29 | | |

## Table 7. Plan 2: Pump and Treat/Soil Vapor Extraction Life-Cycle Costs (5 years)

| | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 |
|---|---|---|---|---|---|
| VOC Extraction Rate (lbs/yr.) | 11,500 | 8,625 | 5,750 | 5,750 | 5,750 |
| Capital Cost | | | | | |
| Site Cost | $7,500 | | | | |
| Equipment Cost | | | | | |
| Design and Engineering | $32,000 | | | | |
| Mobile Equipment | $18,000 | | | | |
| Well Installation | $50,690 | | | | |
| Other Fixed Equipment | $168,665 | | | | |
| Subtotal: Equipment Costs | $276,855 | | | | |
| Mobilization Costs (150 mhrs) | | | | | |
| Technicians (2) | $18,600 | | | | |
| Laborers (2) | $17,400 | | | | |
| Oversight Engineer (1) | $21,300 | | | | |
| Per Diem | $7,313 | | | | |
| Subtotal: Mobilization Costs | $64,613 | | | | |
| Operation and Maintenance Costs | | | | | |
| Monitoring /Maintenance | | | | | |
| Technician | $45,260 | $45,260 | $45,260 | $45,260 | $45,260 |
| Oversight Engineer | $25,915 | $25,915 | $25,915 | $25,915 | $25,915 |
| Subtotal: Monitoring/Maintenance Costs | $71,175 | $71,175 | $71,175 | $71,175 | $71,175 |
| Consumable Costs | | | | | |
| Catalytic Material | $27,500 | $27,500 | $27,500 | $27,500 | $27,500 |
| Electricity — 175 kW/HR ($0.05kWH) | $76,650 | $76,650 | $76,650 | $76,650 | $76,650 |
| Lubricants | $1,095 | $1,095 | $1,095 | $1,095 | $1,095 |
| Maintenance Supplies | $18,350 | $18,350 | $18,350 | $18,350 | $18,350 |
| Subtotal: Consumable Costs | $123,595 | $123,595 | $123,595 | $123,595 | $123,595 |
| Demobilization Costs (150 mhrs) | | | | | |
| Technician (2) | | | | | $18,600 |
| Laborers (2) | | | | | $17,400 |
| Oversight Engineer (1) | | | | | $21,300 |
| Per Diem | | | | | $7,313 |
| Subtotal: Demobilization Costs | | | | | $64,613 |
| TOTAL ANNUAL COSTS | $607,413 | $194,770 | $194,770 | $194,770 | $259,383 |
| TOTAL LIFE CYCLE PRESENT VALUE= (2.3% real discount rate) | $1,402,672 | | | | |
| PRESENT VALUE PER LB VOC REMOVED | $38 | | | | |

## Table 8. Plan 2: Pump and Treat/Soil Vapor Extraction Life-Cycle Costs (10 years)

| | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 | Year 6 | Year 7 | Year 8 | Year 9 | Year 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capital Cost | | | | | | | | | | |
| Site Cost | $7,500 | | | | | | | | | |
| Equipment Cost | | | | | | | | | | |
| Design and Engineering | $32,000 | | | | | | | | | |
| Mobile Equipment | $18,000 | | | | | | | | | |
| Well Installation | $50,690 | | | | | | | | | |
| Other Fixed Equipment | $168,665 | | | | | | | | | |
| Subtotal: Equipment Costs | $276,855 | | | | | | | | | |
| Mobilization Costs (150 mhrs) | | | | | | | | | | |
| Technicians (2) | $18,600 | | | | | | | | | |
| Laborers (2) | $17,400 | | | | | | | | | |
| Oversight Engineer (1) | $21,300 | | | | | | | | | |
| Per Diem | $7,313 | | | | | | | | | |
| Subtotal: Mobilization Costs | $64,613 | | | | | | | | | |
| Operation and Maintenance Costs | | | | | | | | | | |
| Monitoring /Maintenance | | | | | | | | | | |
| Technician | $45,260 | $45,260 | $45,260 | $45,260 | $45,260 | $45,260 | $45,260 | $45,260 | $45,260 | $45,260 |
| Oversight Engineer | $25,915 | $25,915 | $25,915 | $25,915 | $25,915 | $25,915 | $25,915 | $25,915 | $25,915 | $25,915 |
| Subtotal: Monitoring/Maintenance Costs | $71,175 | $71,175 | $71,175 | $71,175 | $71,175 | $71,175 | $71,175 | $71,175 | $71,175 | $71,175 |
| Comsumable Costs | | | | | | | | | | |
| Catalytic Material | $27,500 | $27,500 | $27,500 | $27,500 | $27,500 | $27,500 | $27,500 | $27,500 | $27,500 | $27,500 |
| Electricity | $76,650 | $76,650 | $76,650 | $76,650 | $76,650 | $76,650 | $76,650 | $76,650 | $76,650 | $76,650 |
| Lubricants | $1,095 | $1,095 | $1,095 | $1,095 | $1,095 | $1,095 | $1,095 | $1,095 | $1,095 | $1,095 |
| Maintenance Supplies | $18,250 | $18,250 | $18,250 | $18,250 | $18,250 | $18,250 | $18,250 | $18,250 | $18,250 | $18,250 |
| Subtotal: Consumable Costs | $123,495 | $123,495 | $123,495 | $123,495 | $123,495 | $123,495 | $123,495 | $123,495 | $123,495 | $123,495 |
| Demobilization Costs (150 mhrs) | | | | | | | | | | |
| Technician (2) | | | | | | | | | | $18,600 |
| Laborers (2) | | | | | | | | | | $17,400 |
| Oversight Engineer (1) | | | | | | | | | | $21,300 |
| Per Diem | | | | | | | | | | $7,313 |
| Subtotal: Demobilization Costs | | | | | | | | | | $64,613 |
| TOTAL ANNUAL COSTS | $536,138 | $194,670 | $194,670 | $194,670 | $194,670 | $194,670 | $194,670 | $194,670 | $194,670 | $259,283 |
| TOTAL LIFE CYCLE PRESENT VALUE= | | $2,093,906 | | | | | | | | |

## 7. Cost Sensitivity of ISBR to Biological Component

Since ISBR has such widespread potential for use it would make sense to see how this technology is affected by changes in the biological component. Results obtained from the ISBR demonstration and numerical modeling studies clearly show a bioremediation component of 40% above the amount removed via vacuum extraction [Hazen 94, Travis 94]. While there is no guarantee that this percentage could be obtained in every use of ISBR, it is logical to assume that lessons learned from the ISBR demonstration could be applied to future uses of the technology to obtain biological components well above the current 40%. Several lessons learned from the demonstration include the necessity of injecting both methane and nutrients, while allowing a lag time between injections. Implementation of this process at the beginning of a remediation effort could significantly increase the percentage of VOC destruction due to the biological component, which, in turn lowers the overall cost of remediation and the price per pound of VOCs removed. Data results obtained from the SRID clearly show that the bioremediation process continued for several weeks after the injection of nutrients and methane stopped. It would then seem that while there is a limit due to mass transport which is reached regarding the vacuum component of ISBR, there is no limit to the level of performance which can be obtained via the biological component which is a biochemical process.

To measure the effect on the cost in relation to the biological aspect of ISBR, sensitivity analysis is conducted to determine how the biological aspect affects the cost per pound of VOCs remediated.

### 7.1 Short-term Costs

As mentioned before, ISBR has the potential to out-perform traditional remediation technologies in virtue of its ability to remediate a portion of the contamination *in situ*, thereby eliminating the need to physically remove and destroy the contaminant.

The upper limit of remediation due to the biological component of ISBR is not known at this time. It would seem that at least 40% is reasonable as a result of the ISBR demonstration. The biochemical process of methanotrophic biodegradation occurs underground and there are only limited measurement techniques available to track the process. We can, however, estimate the cost savings of the biological component of ISBR by adding a hypothetical addition of pounds of VOCs removed to the 12,096 pounds of VOCs which were destroyed via the vacuum component. The total cost of equipment, labor and consumables will remain the same; however, the total amount of VOCs remediated will increase, thereby lowering the cost per pound remediated. The following formula shows the relationship of the total cost of ISBR to the cost per pound remediated:

Total Cost for ISBR / (12,096 lbs VOCs + % addition) = new cost per pound VOC remediated

% addition = percentage of additional pounds of VOCs remediated via the biological component of ISBR

We will use six hypothetical percentages to account for a range of new cost per pound of VOCs remediated. The six percentages are 0%, 20%, 40%, 50%, 70%, and 90%. The 0% addition is a **worse case** scenario in which all the components necessary to stimulate the biological aspect are added. However, due to some unknown occurrence, no additional remediation occurs, thereby remediating the site via only the vacuum component. The other five percentages are based on intervals which are evenly spaced between 0 - 100%, with 50% being considered an average possibility. Four possible situations bracketing the 50% addition are included. Table 9 lists the various percent additions and the new cost per pound of VOCs remediated.

**Table 9. Short-term Costs of ISBR with Various Biological Additions (rounded to the nearest dollar)**

| Hypothetical percent addition | Base vacuum component (lbs VOCs) | Pounds Addition (lbs VOCs) | New total pounds VOCs remediated | Price per pound VOC remediated |
|---|---|---|---|---|
| 0% | 12,096 | 0 | 12,096 | $29 |
| 20% | 12,096 | 2,419 | 14,515 | $24 |
| 40% | 12,096 | 4,838 | 16,934 | $21 |
| 50% | 12,096 | 6,048 | 18,144 | $19 |
| 70% | 12,096 | 8,467 | 20,563 | $17 |
| 90% | 12,096 | 10,886 | 22,982 | $15 |

As the pounds of VOCs remediated increases, the price per pound remediated decreases. The short-term ISBR system costs take into account all possible expenses to effect the biological component (equipment, labor, chemical nutrient costs, etc.) during the run. Of particular interest is the worse case scenario, ISBR + 0%. From Table 9 we can see that if we add all the necessary components to stimulate the biological process, and no bioremediation occurs, the cost is $29 per pound of VOCs remediated. Remember from Section 6 that the cost for the baseline pump and treat/soil vapor extraction is $31 per pound of VOCs remediated. What this shows is that even in the worse case scenario ISBR is on-par with the baseline. Even if one adds all the necessary components for the biological addition and no bioremediation occurs, one still has a cost parity with the traditional baseline system. Therefore, it is always beneficial to try to stimulate the biological component if one has the proper site characterization, since there is no cost risk involved if bioremediation does not occur. However, the benefits if the biological component can be stimulated are substantial and should not be overlooked. Figure 6 shows the various hypothetical additions and the decrease in cost per pound remediated. For a complete breakdown of how each cost category changes with the additional remediation, refer to the detailed cost tables located in Appendix B.

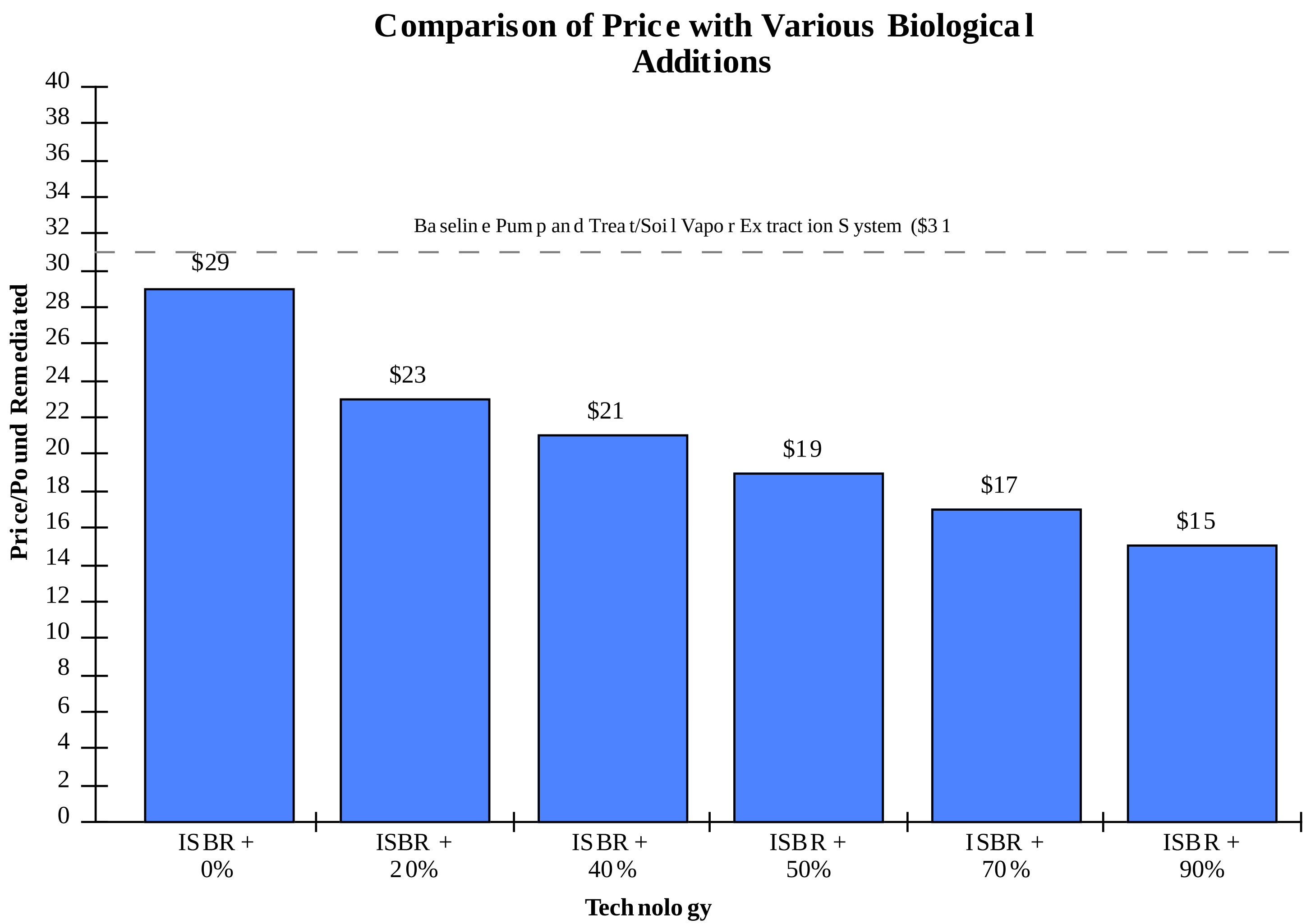



**Figure 6: Cost per pound of VOCs remediated for various biological additions.** The horizontal line represents the conventiona baseline pump and treat/soil vapor extraction. At a cost of $31 per pound of VOCs remediated, even if ISBR has no biological addi (e.g. ISBR +0%), it is still slightly cost effective in comparison to the baseline system. As the biological component increases, the c per pound remediated decreases for ISBR.

### 7.2 Life-Cycle Costs: ISBR with a Biological Addition versus Pump and Treat/Soil Vapor Extraction

Once again we are concerned with determining how the biological component of ISBR affects the associated costs of that technology. As with the short-term costs, the same six hypothetical percent additions of 0%, 20%, 40%, 50%, 70%, and 90% are compared with a traditional pump and treat/soil vapor extraction system.

Rather than having time be the variable component for this life-cycle analysis as we did in Section 6.4, this analysis will keep time constant and vary the amount remediated over equal time between Plan 1 and Plan 2 to see how the quantity remediated over time changes in relation to cost.

Assume for our scenario that due to a regulatory constraint you are being forced to operate a remediation system at the demonstration site for five years. In that five year period you are constrained to remediate as much contamination as possible. From Table 7 we know that Plan 2 will cost $1.4 million to operate, removing 37,375 pounds of VOCs over the five years, giving a cost of $38 per pound of VOC remediate. Table 10 shows us that to operate ISBR over five years also costs 1.4 million. That $1.4 million, however, includes all the necessary equipment to stimulate the biological component. As the biological component increases, the total pounds of VOCs remediated increases and the cost per pound decrease. Table 11 lists the various biological additions and the subsequent costs and pounds remediated.

Again, our worst case scenario of ISBR + 0% shows that if for some reason no biological component occurs, one is no worse off than with the conventional technology (e.g. there is a cost parity of $38 per pound VOCs remediated for either Plan 1 or Plan 2.) The cost for the 5 year operation for both plans is $1.4 million. If both ISBR and PT/SVE only remove the 37,375 pounds of VOCs via vacuum extraction, then a cost parity occurs. But for ISBR, as the biological addition increases, a greater total of VOCs is destroyed for the same cost of $1.4 million, thereby lowering the cost per pound of VOCs remediated. Stimulating a 40% biological addition is at least attainable, as proven by the ISBR demonstration at the SRID, so it is very likely that one could easily increase the total amount of VOCs remediated per given time in comparison to the baseline pump and treat soil vapor extraction system.

### Table 10: Plan 1- In Situ Bioremediation Life-Cycle Costs (5 years)

| | Year 1 | Year 2 | Year 3 | Year 4 | Year 5 |
|---|---|---|---|---|---|
| Capital Cost | | | | | |
| Site Cost | $5,400 | | | | |
| Equipment Cost | | | | | |
| Design and Engineering | $19,200 | | | | |
| Mobile Equipment | $18,000 | | | | |
| Well Installation | $183,000 | | | | |
| Other Fixed Equipment | $183,732 | | | | |
| Subtotal: Equipment Costs | $414,732 | | | | |
| Mobilization Costs (100 mhrs) | | | | | |
| Technicians (2) | $12,400 | | | | |
| Laborers (2) | $11,600 | | | | |
| Oversight Engineer (1) | $14,200 | | | | |
| Per Diem | $4,875 | | | | |
| Subtotal: Mobilization Costs | $43,075 | | | | |
| Operation and Maintenance Costs | | | | | |
| Monitoring /Maintenance | | | | | |
| Technician | $45,260 | $45,260 | $45,260 | $45,260 | $45,260 |
| Oversight Engineer | $25,915 | $25,915 | $25,915 | $25,915 | $25,915 |
| Subtotal: Monitoring/Maintenance Costs | $71,175 | $71,175 | $71,175 | $71,175 | $71,175 |
| Consumable Costs | | | | | |
| Catalytic Material | $22,000 | $22,000 | $22,000 | $22,000 | $22,000 |
| Electricity — 145 kW/HR ($0.05/kWH) | $63,510 | $63,510 | $63,510 | $63,510 | $63,510 |
| Methane (1,323,860 scfm/yr.) | $8,600 | $8,600 | $8,600 | $8,600 | $8,600 |
| Lubricants | $730 | $730 | $730 | $730 | $730 |
| Chemical Additives | $12,775 | $12,775 | $12,775 | $12,775 | $12,775 |
| Maintenance Supplies | $14,600 | $14,600 | $14,600 | $14,600 | $14,600 |
| Subtotal: Consumable Costs | $122,215 | $122,215 | $122,215 | $122,215 | $122,215 |
| Demobilization Costs (100 mhrs) | | | | | |
| Technician (2) | | | | | $12,400 |
| Laborers (2) | | | | | $11,600 |
| Oversight Engineer (1) | | | | | $14,200 |
| Per Diem | | | | | $4,875 |
| Subtotal: Demobilization Costs | | | | | $43,075 |
| TOTAL ANNUAL COSTS | $651,197 | $193,390 | $193,390 | $193,390 | $236,465 |

TOTAL LIFE CYCLE PRESENT VALUE= $1,421,574

(2.3% real discount rate)

**Table 11: Life-Cycle Costs of ISBR (5 years) with Various Biological Additions**

| Hypothetical percent addition | Physical component from Life cycle costs (lbs) | Additional Pounds remediated via biological component | New Total pounds VOCs remediated | Price per pound VOC remediated |
|---|---|---|---|---|
| 0% | 37,375 | 0 | 37,375 | $38 |
| 20% | 37,375 | 7,475 | 44,850 | $31 |
| 40% | 37,375 | 14,950 | 52,325 | $27 |
| 50% | 37,375 | 18,688 | 56,063 | $25 |
| 70% | 37,375 | 26,162 | 63,537 | $22 |
| 90% | 37,375 | 33,638 | 71,013 | $20 |

# 8. Other Considerations

## 8.1. Applicable Geologic Settings

Successful in situ bioremediation requires good contact between the injected air and contaminated soils and groundwater. As such, the optimum geologic setting has the following characteristics [Angell 91]: moderate to high saturated soil permeability, a homogeneous saturated zone, and sufficient saturated thickness. Similarly, optimum characteristics for the vadose zone are high permeability and homogeneity. The physical component of air stripping is generally more effective in coarse-grained soil [Marley 92]. Clay layers, because of their low permeability, are problematic. Typically, though, these are the zones where significant levels of contamination are found, as is the case at the SRID site [Eddy, May 91]. Heterogeneities in the subsurface (either due to stratigraphy or fractures) can result in preferential air flow paths, and thus less effective contact and remediation. If high levels of contaminants are in the clays (low permeability zones) and flow is preferential in high permeability zones, then the clay zones will not be remediated.

ISBR can be very effective in settings where some interbedded thin and/or discontinuous clays are present. ISBR should prove even move successful than in situ air stripping alone because ISBR contains a biological component as well as the physical air stripping process. A potential concern with the use of ISBR is the possible lateral spread of the contaminant plume. If the geology constricts vertical flow, the injection process can push the dissolved contamination concentrically from the injection point [Angell 91]. Thus, it may be advisable in heterogeneous formations to use ISBR in conjunction with a surrounding pump and treat system that provides hydraulic control at the site.

Note that the limitations on applicable geologic settings described above also apply to soil vapor extraction and pump and treat systems [Schroeder 92].

### 8.2 Applicable Waste Sites

According to Schroeder 92, waste sites exhibiting the following characteristics are amenable to remediation using in situ bioremediation provided the necessary conditions named under the checklist for bioremediation have been met (refer to Section 5.1 for checklist):

- Strippable contaminants
  Air sparging involves transport between soil, groundwater and sparged air, so contaminants must be mobile in and between all phases. Contaminants must have a dimensionless Henry's Law constant > 0.01, vapor pressure > 0.1 mm Hg, and soil/water partition coefficient ($K_{OC}$) < 1,000 to be physically removable by sparging (most light hydrocarbons and chlorinated solvents satisfy these conditions) [Angell 91].

- Suitable plume geometry
  Horizontal wells may provide better contact with linearly shaped contaminant plumes. Thin plumes are probably more amenable to the air sparging process. (The geometry of horizontal wells provides better performance than vertical wells when dealing with relatively thin plumes [Langseth 90].) The depth of the plume can also have an effect on the cost effectiveness of ISBR. For shallower plumes, it may be possible to use a less expensive type of drilling method for horizontal wells, such as methods used by the utility or cable industries. A recent modeling study considered the hydraulic performance of horizontal wells for groundwater recovery. This study illustrates that, in many situations, horizontal wells can provide groundwater contaminant recovery performance superior to that available from greater numbers of vertical wells [Langseth 90]. As plumes get thicker, however, or as the vertical hydraulic conductivity decreases, vertical well performance improves relative to horizontal wells [Langseth 90].

- Restricted vertical access
  Horizontal wells have clear technical advantages for reaching under existing structures or features (i.e., buildings, landfills, wetlands, lakes, etc.) to contact contaminated zones that it would not be possible to access using direct vertical drilling above the area of interest. In this sense, the ISAS demonstration showed the utility of using horizontal wells as an access technology. Current plans at the SRID site include the drilling of horizontal wells under the M Area settling basin. Horizontal wells may also be suited for recovering dense non-aqueous phase liquids (DNAPLs) in groundwater [Langseth 90] or above the water table.

- Plume characteristics
  The optimum approach may be to consider ISBR as an effective technique for remediating a "hot spot" (high contaminant source area) that is within a larger plume currently under pump and treat control.

### 8.3 Monitoring Requirements

In full scale application, it is possible that In Situ Bioremediation will have higher monitoring requirements than conventional approaches (e.g., pump and treat). Because the physical stripping of contaminants is occurring *in situ*, some process control is needed to determine the effects in the subsurface. Additional monitoring costs may be necessary, varying from state to state, in order to prove that the bioremediation process is actually occurring in the subsurface. Monitoring requirements can be loosely separated into those required for the vadose zone and those required for the saturated zone. In the vadose zone, monitoring requirements can be expected to be roughly equivalent for Plan 1 versus Plan 2. However, in the saturated zone, the monitoring requirements can be expected to be higher for ISBR versus pump and treat. Because there is the concern that the air/methane injection may spread the contaminant plume, a higher number of monitoring wells surrounding the site may be appropriate. Another consideration used in the demonstration was the use of lower injection rates to minimize the potential for the spread of contaminants. Geophysical or electrical resistance tomography may also be useful to track the movement of injected air [Ramirez 91]. The conventional pump and treat approach has the advantage of providing hydraulic control as part of the remediation strategy.

### 8.4 Health and Safety Issues

There are not any outstanding differences in health and safety issues for Plans 1 and 2. Both include the drilling of wells; safety issues are roughly equivalent for drilling operations for horizontal and vertical wells. Both methods involve escalating worker protection requirements depending on the contaminant level present at the site [NIOSH 85]. Health and safety issues regarding handling of the waste stream at the surface (extracted contaminant vapors and/or water) are also roughly equivalent.

ISBR has an added concern in regards to the injection of methane. Careful monitoring of the injection process is necessary to insure that the explosive limit of methane is not reached. If ISBR can remediate a site in a significantly shorter period of time, then health and safety risks are inherently diminished because of the lower potential for worker exposure.

### 8.5 Regulatory Approval

Regulatory approval requirements are different for ISBR versus the conventional technologies. Because ISBR includes the active injection of air/methane into the subsurface, a permit for this activity is required. At the SRID site, the necessary permit is an Underground Injection Control (UIC) Permit, which is issued by the South Carolina Department of Health and Environmental Control.[6] In acquiring this permit, the SRID was required to address the issue of possible spread of the contaminant plume due to the injected air. The permit was negotiated whereby the ISBR demonstration was designed to always extract air at a higher level than air was injected. Recall that the ISBR demonstration extraction rate was 254 scfm, and air injection rates were 208 scfm. Air was always extracted at a rate higher than the air injection rate. Because ISBR requires an UIC permit and the conventional technologies do not, the time and effort to acquire this permit is a cost that must be considered in an ISBR project.

Both ISBR and the conventional technologies require an air permit for discharge of processed off-gases at the surface. The SRID obtained an Air Permit, required to meet Clean Air Act regulations, from the South Carolina Department of Health and Environmental Control. The permit allows for no more than 9.6 pounds per day of TCE and PCE combined to be released untreated. It should be noted that during the entire ISBR run, the SRID was in compliance with this regulation. Since a cat-ox system was used as an off-gas treatment system and it produces carbon dioxide ($CO_2$) and hydrochloric acid (HCl) as the by-products, additional permits may be required. During the ISBR run, the $CO_2$ and HCl were vented into the air because South Carolina Department of Health and Environmental Control does not require a release permit for an operation of this scale. Modeling done at the site showed that no harm would be done by the venting of these gases. This may not be the case in other states which have stricter air quality regulations than South Carolina, or at a site where the size and scope of the contamination is greater.

The demonstration work at the Savannah River Site is claimed under the Resource Conservation and Recovery Act (RCRA) groundwater corrective action permit.

### 8.6 Technology Optimization

The Earth and Environmental Science group at Los Alamos National Laboratory has designed a computer model of the subsurface processes occurring at Savannah River Site [Robinson 94]. The benefits of such a model allows us to better understand the mechanisms of contaminant transport at work at a specific site. This information can be used to design more effective remediation systems for the given conditions of an area. By conducting modeling experiments, we can cut associated costs by optimizing the operation of the system to avoid a waste of time, labor, consumable material, etc. If we can remediate an area by operating the system for specific times when the amount of contaminants removed is greatest and shutting down the system when no remediation is taking place, we decrease our operating cost, which in turn decreases the cost per pound remediated. In this way, modeling may be used to help guide the design of more efficient remediation systems in the future.

Results from the modeling of the SRID show that continuous injection and extraction for the physical air stripping component of ISBR may not be the most effective choice. Numerical modeling results show that a cyclic injection/extraction schedule, 30 days on, 30 days off, only decreases the overall physical removal rate 35% while cutting the systems operation time in half [Robinson 94]. Our economic analysis shows that, on average, 85% of the costs of either remediation technology is due to consumable and labor costs. These costs are incurred during each day of operation, so if we could cut 85% of the cost per year for half of the time that the remediation system was in use, the savings would be substantial.

Another area in which technology optimization could be used is in the design of the system flow rates. In the past, conventional thought has told us that “bigger is better”; that is, if we design our remediation systems to pull larger flow rates, we could remove a greater amount of contaminants in the same amount of time than smaller systems could. While this logic may be partially true for contaminant transport, it may not be cost effective. Modeling results show that for an increase in flow by a factor of four, there is only a 25% increase in amount of contaminants removed (e.g., if you remove 100 pounds of VOCs at 260 scfm, then at 1040 scfm you only remove 125 pounds of VOCs). But from a cost perspective, as you increase the size of your flow it follows that you must increase the size of your remediation equipment. A general “rule of thumb” for process equipment is that as you increase the size of the equipment, the cost increases logarithmically by a factor of 0.6. Therefore, as an example, a cat-ox system which operates at 260 scfm costs only $57,000 whereas the same system operating at 1040 scfm cost $131,000 [AACE 92].

$$\text{Cost}_{\text{1040 scfm}} = \$57{,}000 \times (1040 \text{ scfm} / 260 \text{ scfm})^{.6} = \$131{,}000$$

This scaling will hold true for most rotating process equipment, so as you increase the size the overall cost to set up the system increases. Therefore, it would seem that a smaller system operating in cyclic intervals would be the most cost-effective way to remediate situations similar to conditions at the SRID.

## 9. Summary

This report examines the cost effectiveness of In Situ Bioremediation (ISBR) with horizontal wells as demonstrated at the Savannah River Integrated Demonstration Site. ISBR is an effective new environmental remediation technology designed to remove chlorinated hydrocarbons from both the vadose and saturated zone. The ISBR system is based on two distinct processes occurring simultaneously: the physical process of air stripping and the biological process of bioremediation. Performance and cost comparisons are made to a conventional pump and treat/soil vapor extraction system. Both systems contained a catalytic-oxidation off-gas treatment system to destroy any volatilized contaminants collected. ISBR is cost sensitive to the biological component's ability to remediate a quantity of contaminants at no additional cost, thereby lowering the cost per pound of VOCs remediated.

In order to stimulate the biological process, a concentration of methane, between 1% and 4% along with the necessary chemical nutrients of nitrogen and phosphorus, were injected into the air stream. This combination provided the raw material necessary for the indigenous microorganisms to degrade the TCE *in situ* via methanotrophic bioremediation.

We assumed that both Plan 1 and Plan 2 were equivalent in vacuum extraction performance and were located in areas of equal site characteristics and contaminant concentration. Field data from the ISBR demonstration provided the necessary information which was applied to both ISBR and the conventional pump and treat/soil vapor extraction system. By doing this, we provided a level playing field for the performance analysis. The data received from the SRID indicated that 12,096 pounds of VOCs were removed in 384 days via the physical component and an additional 40% was destroyed via bioremediation.

The results of the ISBR demonstration at the SRID provided the basis from which the cost- effectiveness analysis was conducted. Plan 1, which is based on the innovative technology ISBR with horizontal wells, remediated 16, 934 pounds of VOCs with a total system costs of $354,000 in the short term, giving a cost of $21 per pound of VOCs remediated. Plan 2, an engineer designed pump and treat/soil vapor extraction, remediates only 12,096 pounds of VOCs in a equal amount of time. The $31 per pound of VOCs remediated is based on a total system cost of $380,000. ISBR, therefore, saves 32% over the conventional baseline system over equal run times of 384 days.

Life-cycle costs for ISBR versus pump and treat/soil vapor extraction are similar to the short-term costs. For the demonstration site in question, it would take the baseline technologies 10 years at a cost of $2 million. ISBR can do the same job in three years at a cost of $1 million, a savings of 50% and 7 years remediation time. If we give the baseline a performance that is twice its predicted potential (i.e. pump and treat/soil vapor extraction remediates the test site in five years), then PT/SVE only costs $1.4 million. ISBR, however, still saves over $400,000 and two years of remediation even given these highly improbable performance results for the baseline technologies.

A sensitivity analysis was conducted to see how the cost per pound remediated is affected by the biological component. In our worst case scenario, ISBR + 0%, there is a cost parity between ISBR and the baseline technologies in both short-term costs and life-cycle costs. What this shows is that even if all the necessary components for the biological aspect of ISBR are added and no bioremediation occurs, one is no worse off relying on the vacuum component of ISBR alone. But the biological component can achieve at least a 40% addition, as proven by the ISBR demonstration, and therefore lowers both the overall time to remediate the site and the cost per pound remediated. It is therefore always desirable to stimulate the biological component since there is no cost risk should no bioremediation occur, and there is a substantial return on investment should bioremediation be stimulated in addition to the vacuum component.

The main cost drivers of both ISBR and pump and treat/soil vapor extraction are labor and consumables. These two cost categories account for 85% of the cost per pound for both technologies. Unlike capital equipment expenses, which can be spread out over the life of a project, consumables and labor must be incurred every day of operation. Therefore, since the site can be remediated significantly faster with a new technology like ISBR, the overall cost of the cleanup is reduced.

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## 11. Acknowledgments

The authors of this paper would like to acknowledge the assistance of the following people in the preparation of this report. They provided valuable insight into the analysis of the problems presented: Terry Hazen, Joe Rossabi, Brian Looney, and Ken Lombard of Westinghouse Savannah River Company for their data and technical support. Peter Barnes-Smith, IT Corporation, for his work on the cost estimates for the remediation systems . Anne Henriksen and Nina Rosenberg of Los Alamos National Laboratory for their input in the analysis of the performance scenario. Michelle Moffitt-Silva of Los Alamos National Laboratory for her assistance in editing, formatting and graphic designs. W. Eric Showalter of Los Alamos National Laboratory for his preliminary research. This report is sponsored by the United States Department of Energy—Office of Technology Development (EM-50) under Technical Task Plan AL-101201.

## 12. Footnotes

[1] Portions of this document are taken from Schroeder 92 with permission of the author.
[2] The pump and treat remediation method is a clear example where early estimates of cleanup times were significantly in error. Because the processes controlling contaminant transport were not well understood, the method was believed to have much higher effectiveness than it has since demonstrated in long term actual use [Hall 91] [Doty 91].
[3] The drinking water standard for TCE is 5 µg/L (5 ppb) and the drinking water standard for PCE is 7 µg/L (7 ppb) [U.S. EPA, July 87].
[4] Adapted from Schneider and Billingsley, 1990.
[5] An estimated cost of $183,000 for the two horizontal wells at the SRID site (of approximately 475 ft total horizontal length) equals ~$385 per foot.
[6] Note that differences will exist between states regarding regulations. The permits required in South Carolina are given here as an example.

# Appendix A

# Cost Estimate Tables:  Sensitivity to Number of SVE Wells

## Appendix A: Cost Estimate Tables-- Sensitivity to Number of SVE Wells

**Table A1 Short term costs for Pump and Treat/Soil Vapor Extraction (2 SVE wells)**

| | | |
|---|---|---|
| PUMP AND TREAT/SOIL VAPOR EXTRACTION (500 scfm) | | |
| Duration (days): | 384 | |
| Lbs VOCs removed: | 12,096 | |
| (4 vertical SVE wells, 1 pump and treat well) | | |
| Annual removal rate (Lbs VOCs) | 11,498 | |
| | *Costs* | *Cost/Lb VOC* |
| *Site Costs* | | |
| Site costs (set up and level area) | $7,500 | |
| Subtotal: Site Costs | $7,500 | |
| Site Cost/Lb VOC Removed | | $0.62 |
| *Equipment Costs* | | |
| Design and engineering {1} (400 mhrs) | $32,000 | |
| Mobile equipment (pickup truck) | $18,000 | |
| Fixed Equipment: Well installation (Pump and Treat) | | |
| Drill and case (1 x 175 ft. x 6" dia x $23.00/lf) | $4,020 | |
| Screens (1 x 6" dia SS @ 35 ft/well x $13.00/lf) | $460 | |
| Sampling (35 samples @ $250 each) | $8,750 | |
| Seals (1 @ 10 sy x $4.00 sy) | $40 | |
| Gravel pack (2.3 cy @ $25/cy) | $60 | |
| Subtotal: Well installation (Pump and Treat) | $13,330 | |
| Fixed Equipment: Well Installation (Soil Vapor Extraction) | | |
| Drill and case (2 x 130' x 4" DIA @ $15/lf) | $3,900 | |
| Screens (2 x 4" DIA PVC x 100' well @ $8/lf) | $1,600 | |
| Sampling (52 samples @ $250 each) | $13,000 | |
| Seals (2 x 10 sy @ $4/sy) | $80 | |
| Gravel Pack (4 cy @ $25/cy) | $100 | |
| Subtotal: Well installation (Soil Vapor Extraction) | $18,680 | |
| Fixed Equipment: Other equipment | | |
| Pump (30 gpm, submerged) | $3,750 | |
| Air stripping tower (30 gpm, 200 cfm, 20" dia) | $9,150 | |
| Cleaning package, control panel, fan | $7,500 | |
| Vapor air separator (1 @ 300 cfm) | $2,000 | |
| Manifold system (4" PVC with valves) | $3,000 | |
| Vapor Extraction Unit (300 scfm) | $13,500 | |
| Catalytic oxidation of f-gas treatment (900˚F , 500 SCFM) | $76,000 | |
| Test/monitor weir | $3,750 | |
| Monitoring equipment | $18,000 | |
| Temporary storage (metal shed) | $1,600 | |
| Piping and insulation (10% of fixed other equipment cost) | $13,825 | |
| Electrical (12% of fixed other equipment cost) | $16,590 | |
| Subtotal: Other equipment | $168,665 | |
| Total Equipment Costs | $250,675 | |
| Amortization fixed charge rate | 0.07 | |
| Site Equipment Costs, one year | $35,690 | |
| Subtotal: Site Equipment Costs during test | $37,548 | |
| Equipment Cost/Lb VOC Removed | | $3.10 |
| *Labor Costs {1}* | | |
| Mobilize/demobilize (based on 300 hrs set up & tear down) | | |
| Technician — 2 | $37,200 | |
| Laborers — 2 | $34,800 | |
| Oversight engineer — 1 | $42,600 | |
| Per diem | $14,625 | |
| Monitoring/maintenance crew | | |
| Technician — 1 (384 days @ 2 hrs/day) | $47,616 | |
| Oversight engineer — 1 (384 days @ 0.5 hrs/days) | $27,264 | |
| Subtotal: Labor Costs | $204,105 | |
| Labor Cost/Lb VOC Removed | | $16.87 |
| *Consumable Costs {2}* | | |
| Catalytic material | $27,500 | |
| Electricity — 175 kW/HR (24 hrs/day) | $80,640 | |
| Lubricants | $1,152 | |
| Maintenance supplies | $19,200 | |
| Subtotal: Consumable Costs | $128,492 | |
| Consumable Cost/Lb VOC Removed | | $10.62 |
| TOTAL SITE COSTS | $377,645 | |
| TOTAL COST/LB VOC REMOVED | | $31.22 |

Notes:

{1} Labor rates per hour (industry averaged): Oversight engineer, $142; Technician, $62; Laborer, $58; Design engineer , $80

{2} Consumable supplies: Catalytic material (initial charge), $27,500; Electricity , $0.05/kWH; Lubricants, $3/day; Maintenance supplies, $50/day.

**Table A2 Short term costs for Pump and Treat/Soil Vapor Extraction (3 SVE wells)**

| | | |
|---|---|---|
| PUMP AND TREAT/SOIL VAPOR EXTRACTION (500 scfm) | | |
| Duration (days): | 384 | |
| Lbs VOCs removed: | 12,096 | |
| (4 vertical SVE wells, 1 pump and treat well) | | |
| Annual removal rate (Lbs VOCs) | 11,498 | |
| | *Costs* | *Cost/Lb VOC* |
| *Site Costs* | | |
| Site costs (set up and level area) | $7,500 | |
| Subtotal: Site Costs | $7,500 | |
| Site Cost/Lb VOC Removed | | $0.62 |
| *Equipment Costs* | | |
| Design and engineering {1} (400 mhrs) | $32,000 | |
| Mobile equipment (pickup truck) | $18,000 | |
| Fixed Equipment: Well installation (Pump and Treat) | | |
| Drill and case (1 x 175 ft. x 6" dia x $23.00/lf) | $4,020 | |
| Screens (1 x 6" dia SS @ 35 ft/well x $13.00/lf) | $460 | |
| Sampling (35 samples @ $250 each) | $8,750 | |
| Seals (1 @ 10 sy x $4.00 sy) | $40 | |
| Gravel pack (2.3 cy @ $25/cy) | $60 | |
| Subtotal: Well installation (Pump and Treat) | $13,330 | |
| Fixed Equipment: Well Installation (Soil Vapor Extraction) | | |
| Drill and case (3 x 130' x 4" DIA @ $15/lf) | $5,850 | |
| Screens (3 x 4" DIA PVC x 100' well @ $8/lf) | $2,400 | |
| Sampling (78 samples @ $250 each) | $19,500 | |
| Seals (3 x 10 sy @ $4/sy) | $120 | |
| Gravel Pack (6 cy @ $25/cy) | $150 | |
| Subtotal: Well installation (Soil Vapor Extraction) | $28,020 | |
| Fixed Equipment: Other equipment | | |
| Pump (30 gpm, submerged) | $3,750 | |
| Air stripping tower (30 gpm, 200 cfm, 20" dia) | $9,150 | |
| Cleaning package, control panel, fan | $7,500 | |
| Vapor air separator (1 @ 300 cfm) | $2,000 | |
| Manifold system (4" PVC with valves) | $3,000 | |
| Vapor Extraction Unit (300 scfm) | $13,500 | |
| Catalytic oxidation of f-gas treatment (900˚F , 500 SCFM) | $76,000 | |
| Test/monitor weir | $3,750 | |
| Monitoring equipment | $18,000 | |
| Temporary storage (metal shed) | $1,600 | |
| Piping and insulation (10% of fixed other equipment cost) | $13,825 | |
| Electrical (12% of fixed other equipment cost) | $16,590 | |
| Subtotal: Other equipment | $168,665 | |
| Total Equipment Costs | $260,015 | |
| Amortization fixed charge rate | 0.07 | |
| Site Equipment Costs, one year | $37,020 | |
| Subtotal: Site Equipment Costs during test | $38,947 | |
| Equipment Cost/Lb VOC Removed | | $3.22 |
| *Labor Costs {1}* | | |
| Mobilize/demobilize (based on 300 hrs set up & tear down) | | |
| Technician — 2 | $37,200 | |
| Laborers — 2 | $34,800 | |
| Oversight engineer — 1 | $42,600 | |
| Per diem | $14,625 | |
| Monitoring/maintenance crew | | |
| Technician — 1 (384 days @ 2 hrs/day) | $47,616 | |
| Oversight engineer — 1 (384 days @ 0.5 hrs/days) | $27,264 | |
| Subtotal: Labor Costs | $204,105 | |
| Labor Cost/Lb VOC Removed | | $16.87 |
| *Consumable Costs {2}* | | |
| Catalytic material | $27,500 | |
| Electricity — 175 kW/HR (24 hrs/day) | $80,640 | |
| Lubricants | $1,152 | |
| Maintenance supplies | $19,200 | |
| Subtotal: Consumable Costs | $128,492 | |
| Consumable Cost/Lb VOC Removed | | $10.62 |
| TOTAL SITE COSTS | $379,044 | |
| TOTAL COST/LB VOC REMOVED | | $31.34 |

Notes:

{1} Labor rates per hour (industry averaged): Oversight engineer, $142; Technician, $62; Laborer, $58; Design engineer , $80

{2} Consumable supplies: Catalytic material (initial charge), $27,500; Electricity, $0.05/kWH; Lubricants, $3/day; Maintenance supplies, $50/day .

**Table A3 Short term costs for Pump and Treat/Soil Vapor Extraction (4 SVE wells)**

| | | |
|---|---|---|
| PUMP AND TREAT/SOIL VAPOR EXTRACTION (500 scfm) | | |
| Duration (days): | 384 | |
| Lbs VOCs removed: | 12,096 | |
| (4 vertical SVE wells, 1 pump and treat well) | | |
| Annual removal rate (Lbs VOCs) | 11,498 | |
| | *Costs* | *Cost/Lb VOC* |
| *Site Costs* | | |
| Site costs (set up and level area) | $7,500 | |
| Subtotal: Site Costs | $7,500 | |
| Site Cost/Lb VOC Removed | | $0.62 |
| *Equipment Costs* | | |
| Design and engineering {1} (400 mhrs) | $32,000 | |
| Mobile equipment (pickup truck) | $18,000 | |
| Fixed Equipment: Well installation (Pump and Treat) | | |
| Drill and case (1 x 175 ft. x 6" dia x $23.00/lf) | $4,020 | |
| Screens (1 x 6" dia SS @ 35 ft/well x $13.00/lf) | $460 | |
| Sampling (35 samples @ $250 each) | $8,750 | |
| Seals (1 @ 10 sy x $4.00 sy) | $40 | |
| Gravel pack (2.3 cy @ $25/cy) | $60 | |
| Subtotal: Well installation (Pump and Treat) | $13,330 | |
| Fixed Equipment: Well Installation (Soil Vapor Extraction) | | |
| Drill and case (4 x 130' x 4" DIA @ $15/lf) | $7,800 | |
| Screens (4 x 4" DIA PVC x 100' well @ $8/lf) | $3,200 | |
| Sampling (104 samples @ $250 each) | $26,000 | |
| Seals (4 x 10 sy @ $4/sy) | $160 | |
| Gravel Pack (8 cy @ $25/cy) | $200 | |
| Subtotal: Well installation (Soil Vapor Extraction) | $37,360 | |
| Fixed Equipment: Other equipment | | |
| Pump (30 gpm, submerged) | $3,750 | |
| Air stripping tower (30 gpm, 200 cfm, 20" dia) | $9,150 | |
| Cleaning package, control panel, fan | $7,500 | |
| Vapor air separator (1 @ 300 cfm) | $2,000 | |
| Manifold system (4" PVC with valves) | $3,000 | |
| Vapor Extraction Unit (300 scfm) | $13,500 | |
| Catalytic oxidation of f-gas treatment (900˚F , 500 SCFM) | $76,000 | |
| Test/monitor weir | $3,750 | |
| Monitoring equipment | $18,000 | |
| Temporary storage (metal shed) | $1,600 | |
| Piping and insulation (10% of fixed other equipment cost) | $13,825 | |
| Electrical (12% of fixed other equipment cost) | $16,590 | |
| Subtotal: Other equipment | $168,665 | |
| Total Equipment Costs | $269,355 | |
| Amortization fixed charge rate | 0.07 | |
| Site Equipment Costs, one year | $38,350 | |
| Subtotal: Site Equipment Costs during test | $40,346 | |
| Equipment Cost/Lb VOC Removed | | $3.34 |
| *Labor Costs {1}* | | |
| Mobilize/demobilize (based on 300 hrs set up & tear down) | | |
| Technician — 2 | $37,200 | |
| Laborers — 2 | $34,800 | |
| Oversight engineer — 1 | $42,600 | |
| Per diem | $14,625 | |
| Monitoring/maintenance crew | | |
| Technician — 1 (384 days @ 2 hrs/day) | $47,616 | |
| Oversight engineer — 1 (384 days @ 0.5 hrs/days) | $27,264 | |
| Subtotal: Labor Costs | $204,105 | |
| Labor Cost/Lb VOC Removed | | $16.87 |
| *Consumable Costs {2}* | | |
| Catalytic material | $27,500 | |
| Electricity — 175 kW/HR (24 hrs/day) | $80,640 | |
| Lubricants | $1,152 | |
| Maintenance supplies | $19,200 | |
| Subtotal: Consumable Costs | $128,492 | |
| Consumable Cost/Lb VOC Removed | | $10.62 |
| TOTAL SITE COSTS | $380,443 | |
| TOTAL COST/LB VOC REMOVED | | $31.45 |

Notes:

{1} Labor rates per hour (industry averaged): Oversight engineer, $142; Technician, $62; Laborer, $58; Design engineer , $80

{2} Consumable supplies: Catalytic material (initial charge), $27,500; Electricity, $0.05/kWH; Lubricants, $3/day; Maintenance supplies, $50/day .

**Table A4 Short term costs for Pump and Treat/Soil Vapor Extraction (5 SVE wells)**

| | | |
|---|---|---|
| PUMP AND TREAT/SOIL VAPOR EXTRACTION (500 scfm) | | |
| Duration (days): | 384 | |
| Lbs VOCs removed: | 12,096 | |
| (4 vertical SVE wells, 1 pump and treat well) | | |
| Annual removal rate (Lbs VOCs) | 11,498 | |
| | *Costs* | *Cost/Lb VOC* |
| *Site Costs* | | |
| Site costs (set up and level area) | $7,500 | |
| Subtotal: Site Costs | $7,500 | |
| Site Cost/Lb VOC Removed | | $0.62 |
| *Equipment Costs* | | |
| Design and engineering {1} (400 mhrs) | $32,000 | |
| Mobile equipment (pickup truck) | $18,000 | |
| Fixed Equipment: Well installation (Pump and Treat) | | |
| Drill and case (1 x 175 ft. x 6" dia x $23.00/lf) | $4,020 | |
| Screens (1 x 6" dia SS @ 35 ft/well x $13.00/lf) | $460 | |
| Sampling (35 samples @ $250 each) | $8,750 | |
| Seals (1 @ 10 sy x $4.00 sy) | $40 | |
| Gravel pack (2.3 cy @ $25/cy) | $60 | |
| Subtotal: Well installation (Pump and Treat) | $13,330 | |
| Fixed Equipment: Well Installation (Soil Vapor Extraction) | | |
| Drill and case (5 x 130' x 4" DIA @ $15/lf) | $9,750 | |
| Screens (5 x 4" DIA PVC x 100' well @ $8/lf) | $4,000 | |
| Sampling (130 samples @ $250 each) | $32,500 | |
| Seals (5 x 10 sy @ $4/sy) | $200 | |
| Gravel Pack (10 cy @ $25/cy) | $250 | |
| Subtotal: Well installation (Soil Vapor Extraction) | $46,700 | |
| Fixed Equipment: Other equipment | | |
| Pump (30 gpm, submerged) | $3,750 | |
| Air stripping tower (30 gpm, 200 cfm, 20" dia) | $9,150 | |
| Cleaning package, control panel, fan | $7,500 | |
| Vapor air separator (1 @ 300 cfm) | $2,000 | |
| Manifold system (4" PVC with valves) | $3,000 | |
| Vapor Extraction Unit (300 scfm) | $13,500 | |
| Catalytic oxidation off-gas treatment (900˚F, 500 SCFM) | $76,000 | |
| Test/monitor weir | $3,750 | |
| Monitoring equipment | $18,000 | |
| Temporary storage (metal shed) | $1,600 | |
| Piping and insulation (10% of fixed other equipment cost) | $13,825 | |
| Electrical (12% of fixed other equipment cost) | $16,590 | |
| Subtotal: Other equipment | $168,665 | |
| Total Equipment Costs | $278,695 | |
| Amortization fixed charge rate | 0.07 | |
| Site Equipment Costs, one year | $39,680 | |
| Subtotal: Site Equipment Costs during test | $41,745 | |
| Equipment Cost/Lb VOC Removed | | $3.45 |
| *Labor Costs {1}* | | |
| Mobilize/demobilize (based on 300 hrs set up & tear down) | | |
| Technician — 2 | $37,200 | |
| Laborers — 2 | $34,800 | |
| Oversight engineer — 1 | $42,600 | |
| Per diem | $14,625 | |
| Monitoring/maintenance crew | | |
| Technician — 1 (384 days @ 2 hrs/day) | $47,616 | |
| Oversight engineer — 1 (384 days @ 0.5 hrs/days) | $27,264 | |
| Subtotal: Labor Costs | $204,105 | |
| Labor Cost/Lb VOC Removed | | $16.87 |
| *Consumable Costs {2}* | | |
| Catalytic material | $27,500 | |
| Electricity — 175 kW/HR (24 hrs/day) | $80,640 | |
| Lubricants | $1,152 | |
| Maintenance supplies | $19,200 | |
| Subtotal: Consumable Costs | $128,492 | |
| Consumable Cost/Lb VOC Removed | | $10.62 |
| TOTAL SITE COSTS | $381,842 | |
| TOTAL COST/LB VOC REMOVED | | $31.57 |

Notes:

{1} Labor rates per hour (industry averaged): Oversight engineer, $142; Technician, $62; Laborer, $58; Design engineer, $80

{2} Consumable supplies: Catalytic material (initial charge), $27,500; Electricity, $0.05/kWH; Lubricants, $3/day; Maintenance supplies, $50/day.

**Table A5 Short term costs for Soil Vapor Extraction (4 SVE wells)**

| | | |
|---|---|---|
| SOIL VAPOR EXTRACTION (300 scfm) | | |
| Duration (days): | 384 | |
| Lbs VOCs removed: | 12,096 | |
| (4 vertical SVE wells, 1 pump and treat well) | | |
| Annual removal rate (Lbs VOCs) | 11,498 | |
| | *Costs* | *Cost/Lb VOC* |
| *Site Costs* | | |
| Site costs (set up and level area) | $7,500 | |
| Subtotal: Site Costs | $7,500 | |
| Site Cost/Lb VOC Removed | | $0.62 |
| *Equipment Costs* | | |
| Design and engineering {1} (400 mhrs) | $32,000 | |
| Mobile equipment (pickup truck) | $18,000 | |
| Fixed Equipment: Well Installation (Soil Vapor Extraction) | | |
| Drill and case (4 x 130' x 4" DIA @ $15/lf) | $7,800 | |
| Screens (4 x 4" DIA PVC x 100' well @ $8/lf) | $3,200 | |
| Sampling (104 samples @ $250 each) | $26,000 | |
| Seals (4 x 10 sy @ $4/sy) | $160 | |
| Gravel Pack (8 cy @ $25/cy) | $200 | |
| Subtotal: Well installation (Soil Vapor Extraction) | $37,360 | |
| Fixed Equipment: Other equipment | | |
| Vapor air separator (1 @ 300 cfm) | $2,000 | |
| Manifold system (4" PVC with valves) | $3,000 | |
| Vapor Extraction Unit (300 scfm) | $13,500 | |
| Catalytic oxidation off-gas treatment (900˚F, 300 SCFM) | $69,000 | |
| Monitoring equipment | $18,000 | |
| Temporary storage (metal shed) | $1,600 | |
| Piping and insulation (10% of fixed other equipment cost) | $10,710 | |
| Electrical (12% of fixed other equipment cost) | $12,852 | |
| Subtotal: Other equipment | $130,662 | |
| Total Equipment Costs | $218,022 | |
| Amortization fixed charge rate | 0.07 | |
| Site Equipment Costs, one year | $31,041 | |
| Subtotal: Site Equipment Costs during test | $32,657 | |
| Equipment Cost/Lb VOC Removed | | $2.70 |
| *Labor Costs {1}* | | |
| Mobilize/demobilize (based on 300 hrs set up & tear down) | | |
| Technician — 2 | $37,200 | |
| Laborers — 2 | $34,800 | |
| Oversight engineer — 1 | $42,600 | |
| Per diem | $14,625 | |
| Monitoring/maintenance crew | | |
| Technician — 1 (384 days @ 2 hrs/day) | $47,616 | |
| Oversight engineer — 1 (384 days @ 0.5 hrs/days) | $27,264 | |
| Subtotal: Labor Costs | $204,105 | |
| Labor Cost/Lb VOC Removed | | $16.87 |
| *Consumable Costs {2}* | | |
| Catalytic material | $27,500 | |
| Electricity — 175 kW/HR (24 hrs/day) | $80,640 | |
| Lubricants | $1,152 | |
| Maintenance supplies | $19,200 | |
| Subtotal: Consumable Costs | $128,492 | |
| Consumable Cost/Lb VOC Removed | | $10.62 |
| TOTAL SITE COSTS | $372,754 | |
| TOTAL COST/LB VOC REMOVED | | $30.82 |

Notes:
{1} Labor rates per hour (industry averaged): Oversight engineer, $142; Technician, $62; Laborer, $58; Design engineer, $80
{2} Consumable supplies: Catalytic material (initial charge), $27,500; Electricity, $0.05/kWH; Lubricants, $3/day; Maintenance supplies, $50/day.

# Appendix B

## Cost Estimate Tables:
## Sensitivity to Biological Component

**Table B1. Short term costs for In Situ Bioremediation with 0% Addition**

| | | |
|---|---|---|
| IN SITU BIOREMEDIATION (ISBR) | | |
| Duration (days): | 384 | |
| Lbs VOCs removed via vacuum component of ISBR | 12,096 | |
| (vacuum base of 12,096 lbs + 0 lbs via biological component) | | |
| Annual removal rate (Lbs VOCs) | 11,498 | |
| | *Costs* | *Cost/Lb VOC* |
| *Site Costs* | | |
| Site costs (set up and level area) | $5,400 | |
| Subtotal: Site Costs | $5,400 | |
| Site Cost/Lb VOC Removed | | $0.45 |
| *Equipment Costs* | | |
| Design and engineering {2} | $19,200 | |
| Mobile equipment (pickup truck) | $18,000 | |
| Fixed equipment—Well installation (subcontracted) {1} | | |
| Air injection well (165 ft. deep, 300 ft. long) | $100,500 | |
| Air extraction well (75 ft. deep, 175 ft. long) | $82,500 | |
| Subtotal: Well installation | $183,000 | |
| Fixed Equipment—Other equipment | | |
| Air injection compressor system (260 cfm) | $18,700 | |
| Air extraction system (530 cfm blower) | $16,100 | |
| Vapor air separator (c/s 1 @ 260 cfm) | $1,700 | |
| Catalytic-oxidation off-gas treatment (900˚ F, 260 cfm) | $57,000 | |
| Methane Blending system | $37,500 | |
| Monitoring equipment | $18,000 | |
| Temporary storage (metal shed) | $1,600 | |
| Piping and insulation (10% of fixed other equipment cost) | $15,060 | |
| Electrical (12% of fixed other equipment cost) | $18,072 | |
| Subtotal: Other equipment | $183,732 | |
| Total Equipment Costs | $403,932 | |
| Amortization fixed charge rate | 0.07 | |
| Site Equipment Costs, one year | $57,511 | |
| Subtotal: Site Equipment Costs during test | $60,505 | |
| Equipment Cost/Lb VOC Removed | | $5.00 |
| *Labor Costs {2}* | | |
| Mobilize/demobilize (based on 200 hrs set up & tear down) | | |
| Technician — 2 | $24,800 | |
| Laborers — 2 | $23,200 | |
| Oversight engineer — 1 | $28,400 | |
| Per diem | $9,750 | |
| Monitoring/maintenance crew | | |
| Technician — 1 (384 days @ 2 hrs/day) | $47,616 | |
| Oversight engineer — 1 (384 days @ 0.5 hrs/day) | $27,264 | |
| Subtotal: Labor Costs | $161,030 | |
| Labor Cost/Lb VOC Removed | | $13.31 |
| *Consumable Costs {3}* | | |
| Catalytic material | $22,000 | |
| Electricity — 145 kW/HR (24 hours/day) | $66,816 | |
| Methane [(natural gas) 1,392,774 scf used by SRS] | $8,979 | |
| Lubricants | $768 | |
| Chemical additives | $13,440 | |
| Maintenance supplies | $15,360 | |
| Subtotal: Consumable Costs | $127,363 | |
| Consumable Cost/Lb VOC Removed | | $10.53 |
| | | |
| TOTAL SITE COSTS | $354,298 | |
| TOTAL COST/LB VOC REMOVED | | $29.29 |

Notes:

{1} Original estimate for wells taken from J. Schroeder memo of 3/24/92 and updated to December 1993 dollars.

{2} Labor rates per hour (industry averaged): Design engineer $80; Oversight engineer, $142; Technician, $62. Laborer, $58.

{3} Consumable supplies: Catalytic material (initial charge), $22,000; Electricity, $0.05/kWH; Chemicals, $35/day Methane @ $0.64469/100scf; Lubricants, $2/day; Maintenance supplies, $40/day

**Table B2. Short term costs for In Situ Bioremediation with 20% Addition**

| | | |
|---|---|---|
| IN SITU BIOREMEDIATION (ISBR) | | |
| Duration (days): | 384 | |
| Lbs VOCs removed via vacuum component of ISBR | 14,515 | |
| (vacuum base of 12,096 lbs + 20% via biological component) | | |
| Annual removal rate (Lbs VOCs) | 13,797 | |
| | *Costs* | *Cost/Lb VOC* |
| *Site Costs* | | |
| Site costs (set up and level area) | $5,400 | |
| Subtotal: Site Costs | $5,400 | |
| Site Cost/Lb VOC Removed | | $0.37 |
| *Equipment Costs* | | |
| Design and engineering {2} | $19,200 | |
| Mobile equipment (pickup truck) | $18,000 | |
| Fixed equipment—Well installation (subcontracted) {1} | | |
| Air injection well (165 ft. deep, 300 ft. long) | $100,500 | |
| Air extraction well (75 ft. deep, 175 ft. long) | $82,500 | |
| Subtotal: Well installation | $183,000 | |
| Fixed Equipment—Other equipment | | |
| Air injection compressor system (260 cfm) | $18,700 | |
| Air extraction system (530 cfm blower) | $16,100 | |
| Vapor air separator (c/s 1 @ 260 cfm) | $1,700 | |
| Catalytic-oxidation off-gas treatment (900˚ F, 260 cfm) | $57,000 | |
| Methane Blending system | $37,500 | |
| Monitoring equipment | $18,000 | |
| Temporary storage (metal shed) | $1,600 | |
| Piping and insulation (10% of fixed other equipment cost) | $15,060 | |
| Electrical (12% of fixed other equipment cost) | $18,072 | |
| Subtotal: Other equipment | $183,732 | |
| Total Equipment Costs | $403,932 | |
| Amortization fixed charge rate | 0.07 | |
| Site Equipment Costs, one year | $57,511 | |
| Subtotal: Site Equipment Costs during test | $60,505 | |
| Equipment Cost/Lb VOC Removed | | $4.17 |
| *Labor Costs {2}* | | |
| Mobilize/demobilize (based on 200 hrs set up & tear down) | | |
| Technician — 2 | $24,800 | |
| Laborers — 2 | $23,200 | |
| Oversight engineer — 1 | $28,400 | |
| Per diem | $9,750 | |
| Monitoring/maintenance crew | | |
| Technician — 1 (384 days @ 2 hrs/day) | $47,616 | |
| Oversight engineer — 1 (384 days @ 0.5 hrs/day) | $27,264 | |
| Subtotal: Labor Costs | $161,030 | |
| Labor Cost/Lb VOC Removed | | $11.09 |
| *Consumable Costs {3}* | | |
| Catalytic material | $22,000 | |
| Electricity — 145 kW/HR (24 hours/day) | $66,816 | |
| Methane [(natural gas) 1,392,774 scf used by SRS] | $8,979 | |
| Lubricants | $768 | |
| Chemical additives | $13,440 | |
| Maintenance supplies | $15,360 | |
| Subtotal: Consumable Costs | $127,363 | |
| Consumable Cost/Lb VOC Removed | | $8.77 |
| TOTAL SITE COSTS | $354,298 | |
| TOTAL COST/LB VOC REMOVED | | $24.41 |

Notes:

{1} Original estimate for wells taken from J. Schroeder memo of 3/24/92 and updated to December 1993 dollars.

{2} Labor rates per hour (industry averaged): Design engineer $80; Oversight engineer, $142; Technician, $62; Laborer, $58.

{3} Consumable supplies: Catalytic material (initial charge), $22,000; Electricity, $0.05/kWH; Chemicals, $35/day Methane @ $0.64469/100scf; Lubricants, $2/day; Maintenance supplies, $40/day

**Table B3. Short term costs for In Situ Bioremediation with 40% Addition**

| | | |
|---|---|---|
| IN SITU BIOREMEDIATION (ISBR) | | |
| Duration (days): | 384 | |
| Lbs VOCs removed via vacuum component of ISBR | 16,934 | |
| (vacuum base of 12,096 lbs + 40% via biological component) | | |
| Annual removal rate (Lbs VOCs) | 16,097 | |
| | *Costs* | *Cost/Lb VOC* |
| *Site Costs* | | |
| Site costs (set up and level area) | $5,400 | |
| Subtotal: Site Costs | $5,400 | |
| Site Cost/Lb VOC Removed | | $0.32 |
| *Equipment Costs* | | |
| Design and engineering {2} | $19,200 | |
| Mobile equipment (pickup truck) | $18,000 | |
| Fixed equipment—Well installation (subcontracted) {1} | | |
| Air injection well (165 ft. deep, 300 ft. long) | $100,500 | |
| Air extraction well (75 ft. deep, 175 ft. long) | $82,500 | |
| Subtotal: Well installation | $183,000 | |
| Fixed Equipment—Other equipment | | |
| Air injection compressor system (260 cfm) | $18,700 | |
| Air extraction system (530 cfm blower) | $16,100 | |
| Vapor air separator (c/s 1 @ 260 cfm) | $1,700 | |
| Catalytic-oxidation off-gas treatment (900˚ F, 260 cfm) | $57,000 | |
| Methane Blending system | $37,500 | |
| Monitoring equipment | $18,000 | |
| Temporary storage (metal shed) | $1,600 | |
| Piping and insulation (10% of fixed other equipment cost) | $15,060 | |
| Electrical (12% of fixed other equipment cost) | $18,072 | |
| Subtotal: Other equipment | $183,732 | |
| Total Equipment Costs | $403,932 | |
| Amortization fixed charge rate | 0.07 | |
| Site Equipment Costs, one year | $57,511 | |
| Subtotal: Site Equipment Costs during test | $60,505 | |
| Equipment Cost/Lb VOC Removed | | $3.57 |
| *Labor Costs {2}* | | |
| Mobilize/demobilize (based on 200 hrs set up & tear down) | | |
| Technician — 2 | $24,800 | |
| Laborers — 2 | $23,200 | |
| Oversight engineer — 1 | $28,400 | |
| Per diem | $9,750 | |
| Monitoring/maintenance crew | | |
| Technician — 1 (384 days @ 2 hrs/day) | $47,616 | |
| Oversight engineer — 1 (384 days @ 0.5 hrs/day) | $27,264 | |
| Subtotal: Labor Costs | $161,030 | |
| Labor Cost/Lb VOC Removed | | $9.51 |
| *Consumable Costs {3}* | | |
| Catalytic material | $22,000 | |
| Electricity — 145 kW/HR (24 hours/day) | $66,816 | |
| Methane [(natural gas) 1,392,774 scf used by SRS] | $8,979 | |
| Lubricants | $768 | |
| Chemical additives | $13,440 | |
| Maintenance supplies | $15,360 | |
| Subtotal: Consumable Costs | $127,363 | |
| Consumable Cost/Lb VOC Removed | | $7.52 |
| TOTAL SITE COSTS | $354,298 | |
| TOTAL COST/LB VOC REMOVED | | $20.92 |

Notes:

{1} Original estimate for wells taken from J. Schroeder memo of 3/24/92 and updated to December 1993 dollars.

{2} Labor rates per hour (industry averaged): Design engineer $80; Oversight engineer, $142; Technician, $62. Laborer, $58.

{3} Consumable supplies: Catalytic material (initial charge), $22,000; Electricity, $0.05/kWH; Chemicals, $35/day Methane @ $0.64469/100scf; Lubricants, $2/day; Maintenance supplies, $40/day

**Table B4. Short term costs for In Situ Bioremediation with 50% Addition**

| | | |
|---|---|---|
| IN SITU BIOREMEDIATION (ISBR) | | |
| Duration (days): | 384 | |
| Lbs VOCs removed via vacuum component of ISBR | 18,144 | |
| (vacuum base of 12,096 lbs + 50% via biological component) | | |
| Annual removal rate (Lbs VOCs) | 17,246 | |
| | *Costs* | *Cost/Lb VOC* |
| *Site Costs* | | |
| Site costs (set up and level area) | $5,400 | |
| Subtotal: Site Costs | $5,400 | |
| Site Cost/Lb VOC Removed | | $0.30 |
| *Equipment Costs* | | |
| Design and engineering {2} | $19,200 | |
| Mobile equipment (pickup truck) | $18,000 | |
| Fixed equipment—Well installation (subcontracted) {1} | | |
| Air injection well (165 ft. deep, 300 ft. long) | $100,500 | |
| Air extraction well (75 ft. deep, 175 ft. long) | $82,500 | |
| Subtotal: Well installation | $183,000 | |
| Fixed Equipment—Other equipment | | |
| Air injection compressor system (260 cfm) | $18,700 | |
| Air extraction system (530 cfm blower) | $16,100 | |
| Vapor air separator (c/s 1 @ 260 cfm) | $1,700 | |
| Catalytic-oxidation off-gas treatment (900˚ F, 260 cfm) | $57,000 | |
| Methane Blending system | $37,500 | |
| Monitoring equipment | $18,000 | |
| Temporary storage (metal shed) | $1,600 | |
| Piping and insulation (10% of fixed other equipment cost) | $15,060 | |
| Electrical (12% of fixed other equipment cost) | $18,072 | |
| Subtotal: Other equipment | $183,732 | |
| Total Equipment Costs | $403,932 | |
| Amortization fixed charge rate | 0.07 | |
| Site Equipment Costs, one year | $57,511 | |
| Subtotal: Site Equipment Costs during test | $60,505 | |
| Equipment Cost/Lb VOC Removed | | $3.33 |
| *Labor Costs {2}* | | |
| Mobilize/demobilize (based on 200 hrs set up & tear down) | | |
| Technician — 2 | $24,800 | |
| Laborers — 2 | $23,200 | |
| Oversight engineer — 1 | $28,400 | |
| Per diem | $9,750 | |
| Monitoring/maintenance crew | | |
| Technician — 1 (384 days @ 2 hrs/day) | $47,616 | |
| Oversight engineer — 1 (384 days @ 0.5 hrs/day) | $27,264 | |
| Subtotal: Labor Costs | $161,030 | |
| Labor Cost/Lb VOC Removed | | $8.88 |
| *Consumable Costs {3}* | | |
| Catalytic material | $22,000 | |
| Electricity — 145 kW/HR (24 hours/day) | $66,816 | |
| Methane [(natural gas) 1,392,774 scf used by SRS] | $8,979 | |
| Lubricants | $768 | |
| Chemical additives | $13,440 | |
| Maintenance supplies | $15,360 | |
| Subtotal: Consumable Costs | $127,363 | |
| Consumable Cost/Lb VOC Removed | | $7.02 |
| TOTAL SITE COSTS | $354,298 | |
| TOTAL COST/LB VOC REMOVED | | $19.53 |

Notes:

{1} Original estimate for wells taken from J. Schroeder memo of 3/24/92 and updated to December 1993 dollars.

{2} Labor rates per hour (industry averaged): Design engineer $80; Oversight engineer, $142; Technician, $62. Laborer, $58.

{3} Consumable supplies: Catalytic material (initial charge), $22,000; Electricity, $0.05/kWH; Chemicals, $35/day Methane @ $0.64469/100scf; Lubricants, $2/day; Maintenance supplies, $40/day

**Table B5. Short term costs for In Situ Bioremediation with 70% Addition**

| | | |
|---|---|---|
| Duration (days): | 384 | |
| Lbs VOCs removed via vacuum component of ISBR | 20,563 | |
| (vacuum base of 12,096 lbs + 70% via biological component) | | |
| Annual removal rate (Lbs VOCs) | 19,546 | |
| | *Costs* | *Cost/Lb VOC* |
| *Site Costs* | | |
| Site costs (set up and level area) | $5,400 | |
| Subtotal: Site Costs | $5,400 | |
| Site Cost/Lb VOC Removed | | $0.26 |
| *Equipment Costs* | | |
| Design and engineering {2} | $19,200 | |
| Mobile equipment (pickup truck) | $18,000 | |
| Fixed equipment—Well installation (subcontracted) {1} | | |
| Air injection well (165 ft. deep, 300 ft. long) | $100,500 | |
| Air extraction well (75 ft. deep, 175 ft. long) | $82,500 | |
| Subtotal: Well installation | $183,000 | |
| Fixed Equipment—Other equipment | | |
| Air injection compressor system (260 cfm) | $18,700 | |
| Air extraction system (530 cfm blower) | $16,100 | |
| Vapor air separator (c/s 1 @ 260 cfm) | $1,700 | |
| Catalytic-oxidation off-gas treatment (900˚ F, 260 cfm) | $57,000 | |
| Methane Blending system | $37,500 | |
| Monitoring equipment | $18,000 | |
| Temporary storage (metal shed) | $1,600 | |
| Piping and insulation (10% of fixed other equipment cost) | $15,060 | |
| Electrical (12% of fixed other equipment cost) | $18,072 | |
| Subtotal: Other equipment | $183,732 | |
| Total Equipment Costs | $403,932 | |
| Amortization fixed charge rate | 0.07 | |
| Site Equipment Costs, one year | $57,511 | |
| Subtotal: Site Equipment Costs during test | $60,505 | |
| Equipment Cost/Lb VOC Removed | | $2.94 |
| *Labor Costs {2}* | | |
| Mobilize/demobilize (based on 200 hrs set up & tear down) | | |
| Technician — 2 | $24,800 | |
| Laborers — 2 | $23,200 | |
| Oversight engineer — 1 | $28,400 | |
| Per diem | $9,750 | |
| Monitoring/maintenance crew | | |
| Technician — 1 (384 days @ 2 hrs/day) | $47,616 | |
| Oversight engineer — 1 (384 days @ 0.5 hrs/day) | $27,264 | |
| Subtotal: Labor Costs | $161,030 | |
| Labor Cost/Lb VOC Removed | | $7.83 |
| *Consumable Costs {3}* | | |
| Catalytic material | $22,000 | |
| Electricity — 145 kW/HR (24 hours/day) | $66,816 | |
| Methane [(natural gas) 1,392,774 scf used by SRS] | $8,979 | |
| Lubricants | $768 | |
| Chemical additives | $13,440 | |
| Maintenance supplies | $15,360 | |
| Subtotal: Consumable Costs | $127,363 | |
| Consumable Cost/Lb VOC Removed | | $6.19 |
| TOTAL SITE COSTS | $354,298 | |
| TOTAL COST/LB VOC REMOVED | | $17.23 |

Notes:
{1} Original estimate for wells taken from J. Schroeder memo of 3/24/92 and updated to December 1993 dollars.
{2} Labor rates per hour (industry averaged): Design engineer $80; Oversight engineer, $142; Technician, $62. Laborer, $58.
{3} Consumable supplies: Catalytic material (initial charge), $22,000; Electricity, $0.05/kWH; Chemicals, $35/day Methane @ $0.64469/100scf; Lubricants, $2/day; Maintenance supplies, $40/day

**Table B6. Short term costs for In Situ Bioremediation with 90% Addition**

| | | |
|---|---|---|
| Duration (days): | 384 | |
| Lbs VOCs removed via vacuum component of ISBR | 22,982 | |
| (vacuum base of 12,096 lbs + 90% via biological component) | | |
| Annual removal rate (Lbs VOCs) | 21,845 | |
| | *Costs* | *Cost/Lb VOC* |
| *Site Costs* | | |
| Site costs (set up and level area) | <u>$5,400</u> | |
| Subtotal: Site Costs | $5,400 | |
| Site Cost/Lb VOC Removed | | $0.23 |
| *Equipment Costs* | | |
| Design and engineering {2} | $19,200 | |
| Mobile equipment (pickup truck) | $18,000 | |
| Fixed equipment—Well installation (subcontracted) {1} | | |
| Air injection well (165 ft. deep, 300 ft. long) | $100,500 | |
| Air extraction well (75 ft. deep, 175 ft. long) | <u>$82,500</u> | |
| Subtotal: Well installation | $183,000 | |
| Fixed Equipment—Other equipment | | |
| Air injection compressor system (260 cfm) | $18,700 | |
| Air extraction system (530 cfm blower) | $16,100 | |
| Vapor air separator (c/s 1 @ 260 cfm) | $1,700 | |
| Catalytic-oxidation off-gas treatment (900˚ F, 260 cfm) | $57,000 | |
| Methane Blending system | $37,500 | |
| Monitoring equipment | $18,000 | |
| Temporary storage (metal shed) | $1,600 | |
| Piping and insulation (10% of fixed other equipment cost) | $15,060 | |
| Electrical (12% of fixed other equipment cost) | <u>$18,072</u> | |
| Subtotal: Other equipment | $183,732 | |
| Total Equipment Costs | $403,932 | |
| Amortization fixed charge rate | 0.07 | |
| Site Equipment Costs, one year | $57,511 | |
| Subtotal: Site Equipment Costs during test | $60,505 | |
| Equipment Cost/Lb VOC Removed | | $2.63 |
| *Labor Costs {2}* | | |
| Mobilize/demobilize (based on 200 hrs set up & tear down) | | |
| Technician — 2 | $24,800 | |
| Laborers — 2 | $23,200 | |
| Oversight engineer — 1 | $28,400 | |
| Per diem | $9,750 | |
| Monitoring/maintenance crew | | |
| Technician — 1 (384 days @ 2 hrs/day) | $47,616 | |
| Oversight engineer — 1 (384 days @ 0.5 hrs/day) | <u>$27,264</u> | |
| Subtotal: Labor Costs | $161,030 | |
| Labor Cost/Lb VOC Removed | | $7.01 |
| *Consumable Costs {3}* | | |
| Catalytic material | $22,000 | |
| Electricity — 145 kW/HR (24 hours/day) | $66,816 | |
| Methane [(natural gas) 1,392,774 scf used by SRS] | $8,979 | |
| Lubricants | $768 | |
| Chemical additives | $13,440 | |
| Maintenance supplies | <u>$15,360</u> | |
| Subtotal: Consumable Costs | $127,363 | |
| Consumable Cost/Lb VOC Removed | | $5.54 |
| TOTAL SITE COSTS | $354,298 | |
| TOTAL COST/LB VOC REMOVED | | $15.42 |

Notes:

{1} Original estimate for wells taken from J. Schroeder memo of 3/24/92 and updated to December 1993 dollars.

{2} Labor rates per hour (industry averaged): Design engineer $80; Oversight engineer, $142; Technician, $62. Laborer, $58.

{3} Consumable supplies: Catalytic material (initial charge), $22,000; Electricity, $0.05/kWH; Chemicals, $35/day Methane @ $0.64469/100scf; Lubricants, $2/day; Maintenance supplies, $40/day

# Appendix C

# Cost Estimate Tables: Catalytic-Oxidation vs. GAC

### C1 Short term costs for In Situ Air Stripping (CAT-OX)

| | | |
|---|---|---|
| Duration (days): | 139 | |
| Lbs VOCs removed | 16,000 | |
| Annual removal rate (Lbs VOCs) | 33,612 | |
| | *Costs* | *Cost/Lb VOC* |
| *Site Costs* | | |
| Site costs (set up and level area) | $5,400 | |
| Subtotal: Site Costs | $5,400 | |
| Site Cost/Lb VOC Removed | | $0.34 |
| *Equipment Costs* | | |
| Design and engineering {2} (240 mhrs.) | $19,200 | |
| Mobile equipment (pickup truck) | $18,000 | |
| Fixed equipment—Well installation (subcontracted) {1} | | |
| Air injection well (165 ft. deep, 300 ft. long) | $100,500 | |
| Air extraction well (75 ft. deep, 175 ft. long) | $82,500 | |
| Subtotal: Well installation | $183,000 | |
| Fixed Equipment—Other equipment | | |
| Air injection compressor system (360 cfm) | $19,500 | |
| Air extraction system (530 cfm blower) | $16,100 | |
| Vapor air separator (c/s 1 @ 530 cfm) | $2,750 | |
| Catalytic-oxidation off-gas treatment (900˚ F, 350 cfm) | $60,800 | |
| Monitoring equipment | $18,000 | |
| Temporary storage (metal shed) | $1,600 | |
| Piping and insulation (10% of fixed other equipment cost) | $11,875 | |
| Electrical (12% of fixed other equipment cost) | $14,250 | |
| Subtotal: Other equipment | $144,875 | |
| Total Equipment Costs | $365,075 | |
| Amortization fixed charge rate | 0.07 | |
| Subtotal: Site Equipment Costs | $51,979 | |
| Equipment Cost/Lb VOC Removed | | $3.25 |
| *Labor Costs {2}* | | |
| Mobilize/demobilize (based on 200 hrs set up & tear down) | | |
| Technician — 2 | $24,800 | |
| Laborers — 2 | $23,200 | |
| Oversight engineer — 1 | $28,400 | |
| Per diem | $9,750 | |
| Monitoring/maintenance crew | | |
| Technician — 1 (139 days @ 2 hrs/day) | $17,236 | |
| Oversight engineer — 1 (139 days @ 0.5 hrs/day) | $9,869 | |
| Subtotal: Labor Costs | $113,255 | |
| Labor Cost/Lb VOC Removed | | $7.08 |
| *Consumable Costs {3}* | | |
| Catalytic material | $22,000 | |
| Electricity — 145 kW/HR (24 hours/day) | $24,186 | |
| Lubricants | $278 | |
| Maintenance supplies | $5,560 | |
| Subtotal: Consumable Costs | $52,024 | |
| Consumable Cost/Lb VOC Removed | | $3.25 |
| TOTAL SITE COSTS | $222,658 | |
| TOTAL COST/LB VOC REMOVED | | $13.92 |

Notes:

{1} Original estimate for wells taken from J. Schroeder memo of 3/24/92 and updated to December 1993 dollars.

{2} Labor rates per hour (industry averaged): Design engineer $80; Oversight engineer, $142; Technician, $62. Laborer, $58.

{3} Consumable supplies: Catalytic material (initial charge), $22,000; Electricity, $0.05 kWH; Lubricants, $2/day; Maintenance supplies, $40/day

### C2 Short term costs for In Situ Air Stripping (GAC low cost)

| | | |
|---|---|---|
| IN SITU AIR STRIPPING (ISAS) with GAC (Carbon at $1.50/lb) | | |
| Duration (days): | 139 | |
| Lbs VOCs removed | 16,000 | |
| Annual removal rate (Lbs VOCs) | 33,612 | |
| | *Costs* | *Cost/Lb VOC* |
| *Site Costs* | | |
| Site costs (set up and level area) | $5,400 | |
| Subtotal: Site Costs | $5,400 | |
| Site Cost/Lb VOC Removed | | $0.34 |
| *Equipment Costs* | | |
| Design and engineering {2} (240 mhrs.) | $19,200 | |
| Mobile equipment (pickup truck) | $18,000 | |
| Fixed equipment—Well installation (subcontracted) {1} | | |
| Air injection well (165 ft. deep, 300 ft. long) | $100,500 | |
| Air extraction well (75 ft. deep, 175 ft. long) | $82,500 | |
| Subtotal: Well installation | $183,000 | |
| Fixed Equipment—Other equipment | | |
| Air injection compressor system (360 cfm) | $19,500 | |
| Air extraction system (530 cfm blower) | $16,100 | |
| Vapor air separator (c/s 1 @ 530 cfm) | $2,750 | |
| Carbon Adsorbtion Unit (2 x 600 cfm calgon cannisters) | $10,200 | |
| Monitoring equipment | $18,000 | |
| Temporary storage (metal shed) | $1,600 | |
| Piping and insulation (10% of fixed other equipment cost) | $6,815 | |
| Electrical (12% of fixed other equipment cost) | $8,178 | |
| Subtotal: Other equipment | $83,143 | |
| Total Equipment Costs | $303,343 | |
| Amortization fixed charge rate | 0.07 | |
| Subtotal: Site Equipment Costs | $43,190 | |
| Equipment Cost/Lb VOC Removed | | $2.70 |
| *Labor Costs {2}* | | |
| Mobilize/demobilize (based on 200 hrs set up & tear down) | | |
| Technician — 2 | $24,800 | |
| Laborers — 2 | $23,200 | |
| Oversight engineer — 1 | $28,400 | |
| Per diem | $9,750 | |
| Monitoring/maintenance crew | | |
| Technician — 1 (139 days @ 2 hrs/day) | $17,236 | |
| Oversight engineer — 1 (139 days @ 0.5 hrs/day) | $9,869 | |
| Subtotal: Labor Costs | $113,255 | |
| Labor Cost/Lb VOC Removed | | $7.08 |
| *Consumable Costs {3}* | | |
| Carbon recharge (2.23 LBS Carbon/LB VOC) | $53,520 | |
| Electricity — 145 kW/HR (24 hours/day) | $24,186 | |
| Lubricants | $278 | |
| Maintenance supplies | $5,560 | |
| Subtotal: Consumable Costs | $83,544 | |
| Consumable Cost/Lb VOC Removed | | $5.22 |
| TOTAL SITE COSTS | $245,389 | |
| TOTAL COST/LB VOC REMOVED | | $15.34 |

Notes:

{1} Original estimate for wells taken from J. Schroeder memo of 3/24/92 and updated to December 1993 dollars.

{2} Labor rates per hour (industry averaged): Design engineer $80; Oversight engineer, $142; Technician, $62. Laborer, $58.

{3} Consumable supplies: Carbon, $1.50/lb; Electricity, $0.05 kWH; Lubricants, $2/day; Maintenance supplies, $40/day

### C3 Short term costs for In Situ Air Stripping (GAC high cost)

| | | |
|---|---|---|
| IN SITU AIR STRIPPING (ISAS) with GAC (Carbon at $3.00/lb) | | |
| Duration (days): | 139 | |
| Lbs VOCs removed | 16,000 | |
| Annual removal rate (Lbs VOCs) | 33,612 | |
| | *Costs* | *Cost/Lb VOC* |
| *Site Costs* | | |
| Site costs (set up and level area) | $5,400 | |
| Subtotal: Site Costs | $5,400 | |
| Site Cost/Lb VOC Removed | | $0.34 |
| *Equipment Costs* | | |
| Design and engineering {2} (240 mhrs.) | $19,200 | |
| Mobile equipment (pickup truck) | $18,000 | |
| Fixed equipment—Well installation (subcontracted) {1} | | |
| Air injection well (165 ft. deep, 300 ft. long) | $100,500 | |
| Air extraction well (75 ft. deep, 175 ft. long) | $82,500 | |
| Subtotal: Well installation | $183,000 | |
| Fixed Equipment—Other equipment | | |
| Air injection compressor system (360 cfm) | $19,500 | |
| Air extraction system (530 cfm blower) | $16,100 | |
| Vapor air separator (c/s 1 @ 530 cfm) | $2,750 | |
| Carbon Adsorbtion Unit (2 x 600 cfm calgon cannisters) | $10,200 | |
| Monitoring equipment | $18,000 | |
| Temporary storage (metal shed) | $1,600 | |
| Piping and insulation (10% of fixed other equipment cost) | $6,815 | |
| Electrical (12% of fixed other equipment cost) | $8,178 | |
| Subtotal: Other equipment | $83,143 | |
| Total Equipment Costs | $303,343 | |
| Amortization fixed charge rate | 0.07 | |
| Subtotal: Site Equipment Costs | $43,190 | |
| Equipment Cost/Lb VOC Removed | | $2.70 |
| *Labor Costs {2}* | | |
| Mobilize/demobilize (based on 200 hrs set up & tear down) | | |
| Technician — 2 | $24,800 | |
| Laborers — 2 | $23,200 | |
| Oversight engineer — 1 | $28,400 | |
| Per diem | $9,750 | |
| Monitoring/maintenance crew | | |
| Technician — 1 (139 days @ 2 hrs/day) | $17,236 | |
| Oversight engineer — 1 (139 days @ 0.5 hrs/day) | $9,869 | |
| Subtotal: Labor Costs | $113,255 | |
| Labor Cost/Lb VOC Removed | | $7.08 |
| *Consumable Costs {3}* | | |
| Carbon recharge (2.23 LBS Carbon/LB VOC) | $107,040 | |
| Electricity — 145 kW/HR (24 hours/day) | $24,186 | |
| Lubricants | $278 | |
| Maintenance supplies | $5,560 | |
| Subtotal: Consumable Costs | $137,064 | |
| Consumable Cost/Lb VOC Removed | | $8.57 |
| TOTAL SITE COSTS | $298,909 | |
| TOTAL COST/LB VOC REMOVED | | $18.68 |

Notes:

{1} Original estimate for wells taken from J. Schroeder memo of 3/24/92 and updated to December 1993 dollars.

{2} Labor rates per hour (industry averaged): Design engineer $80; Oversight engineer, $142; Technician, $62. Laborer, $58.

{3} Consumable supplies: Carbon, $3.00 lb; Electricity, $0.05/kWH; Lubricants, $2/day; Maintenance supplies, $40/day

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